SuperCDMS: Design Drivers, R&D Progress, and the Future

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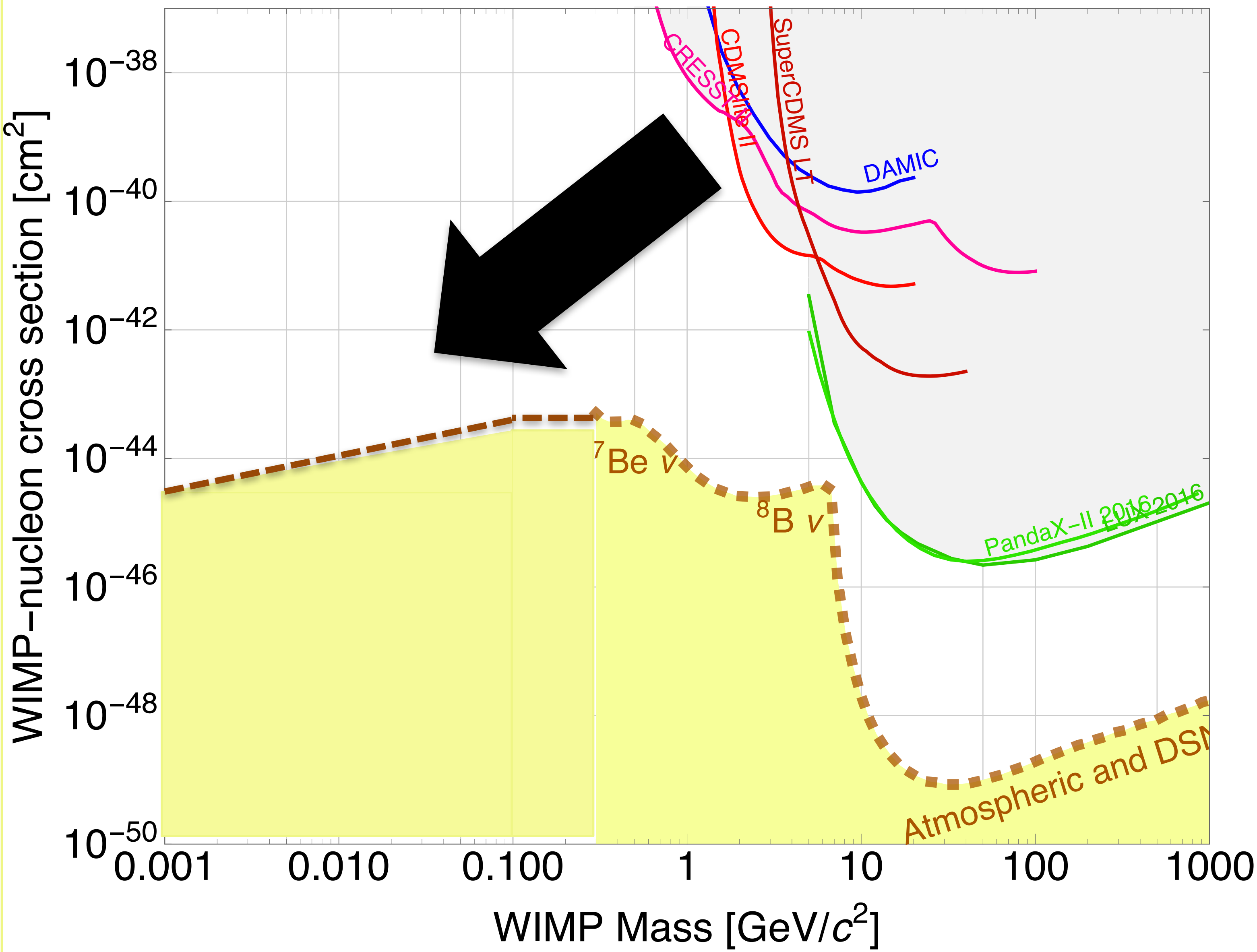
12/6/16

3rd Dark Matter Workshop

LBL

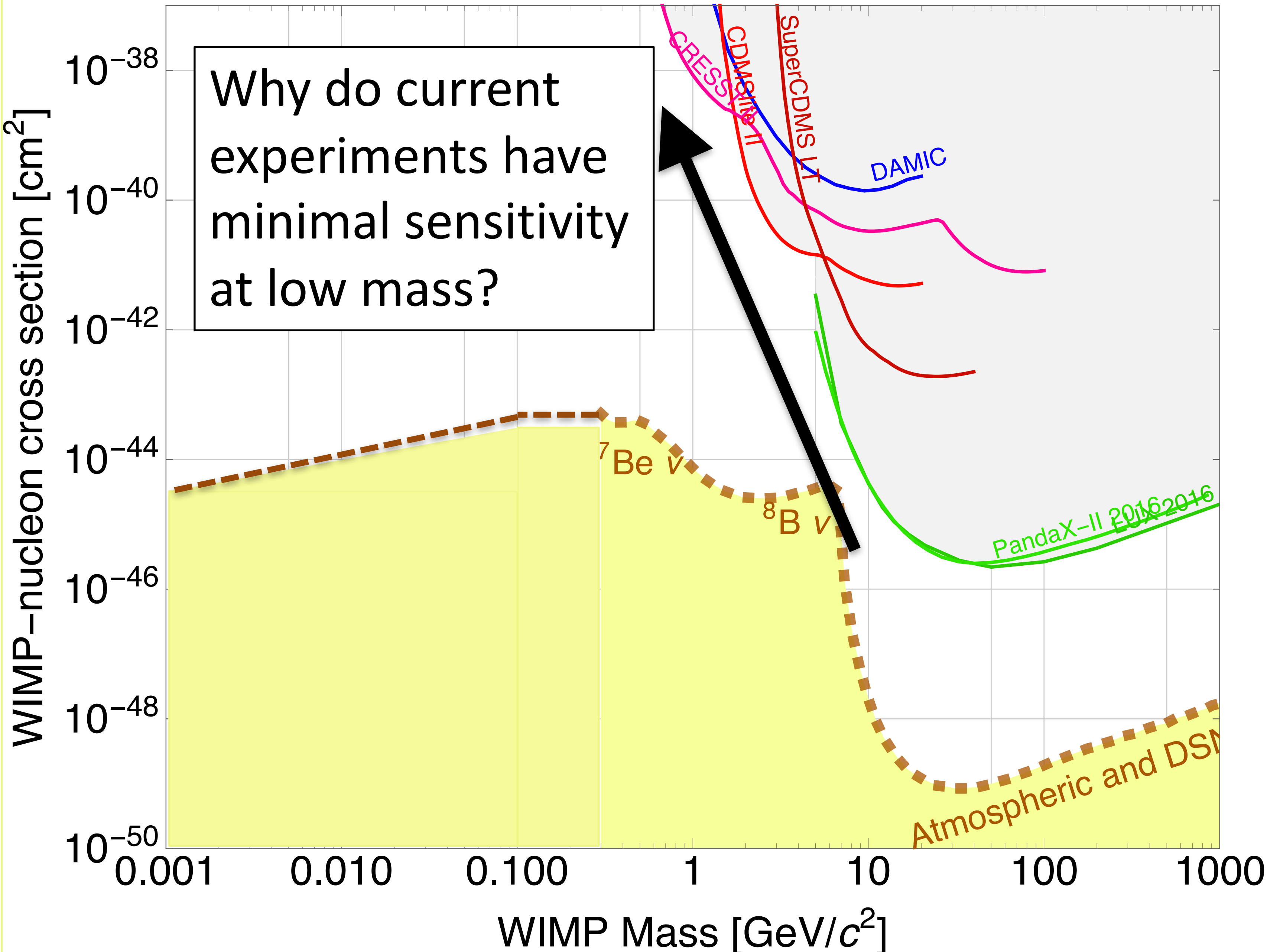
How Do We Extend the Reach of Direct Detection Experiments?



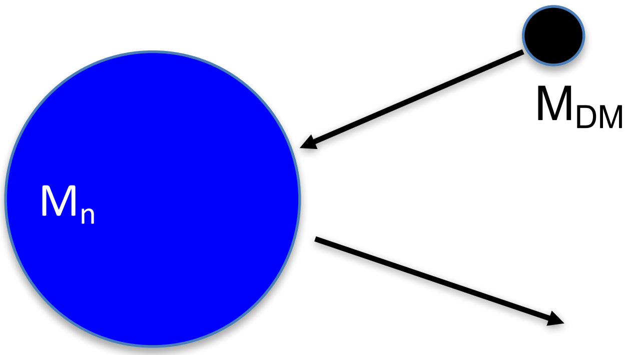
Plan

- Design Drivers for Light Mass Dark Matter Detectors (300 MeV < M_{DM}<10 GeV)
  - He vs Ge
- SuperCDMS Experiment
  - Design
  - R&D Progress
  - Sensitivity Estimates
    - Sensitivity to Nuclear Recoil ionization yield
    - Sensitivity to Dark Currents
- Beyond G2

Current Status: Elastic Nuclear Recoil Direct Detection

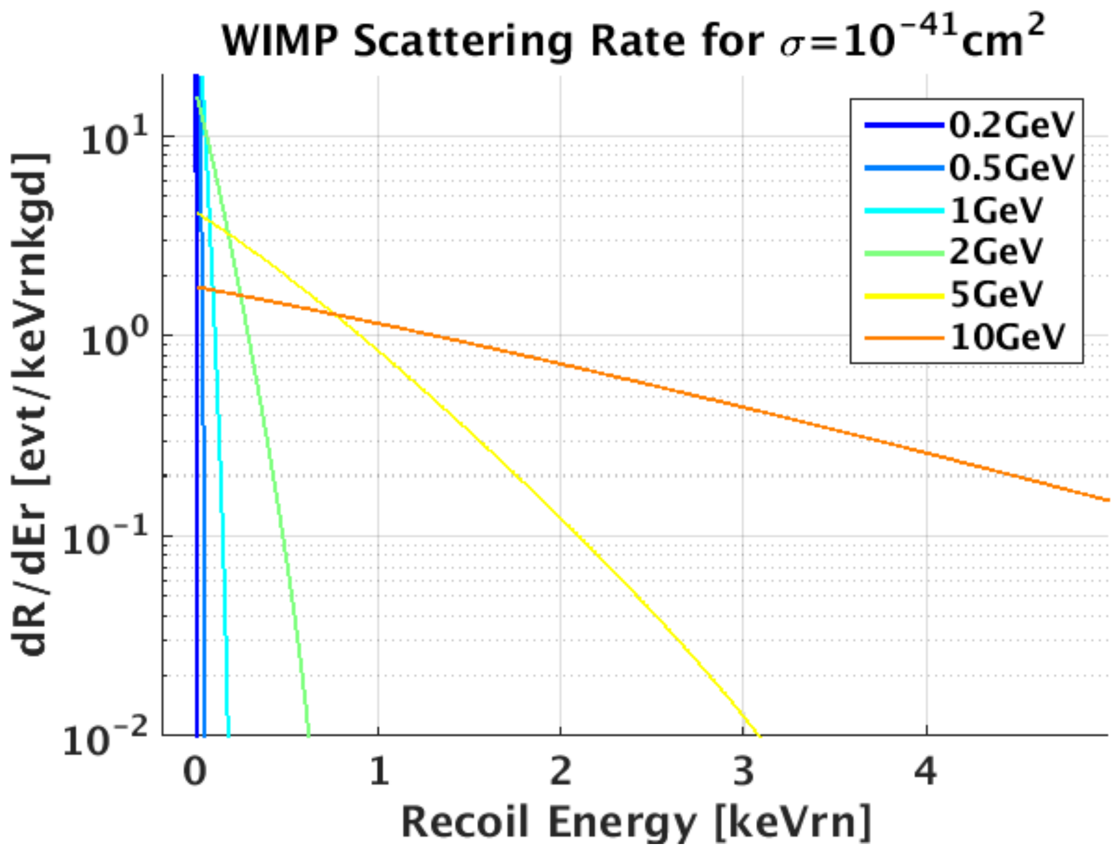


Problem 1: Tiny Recoil Energies



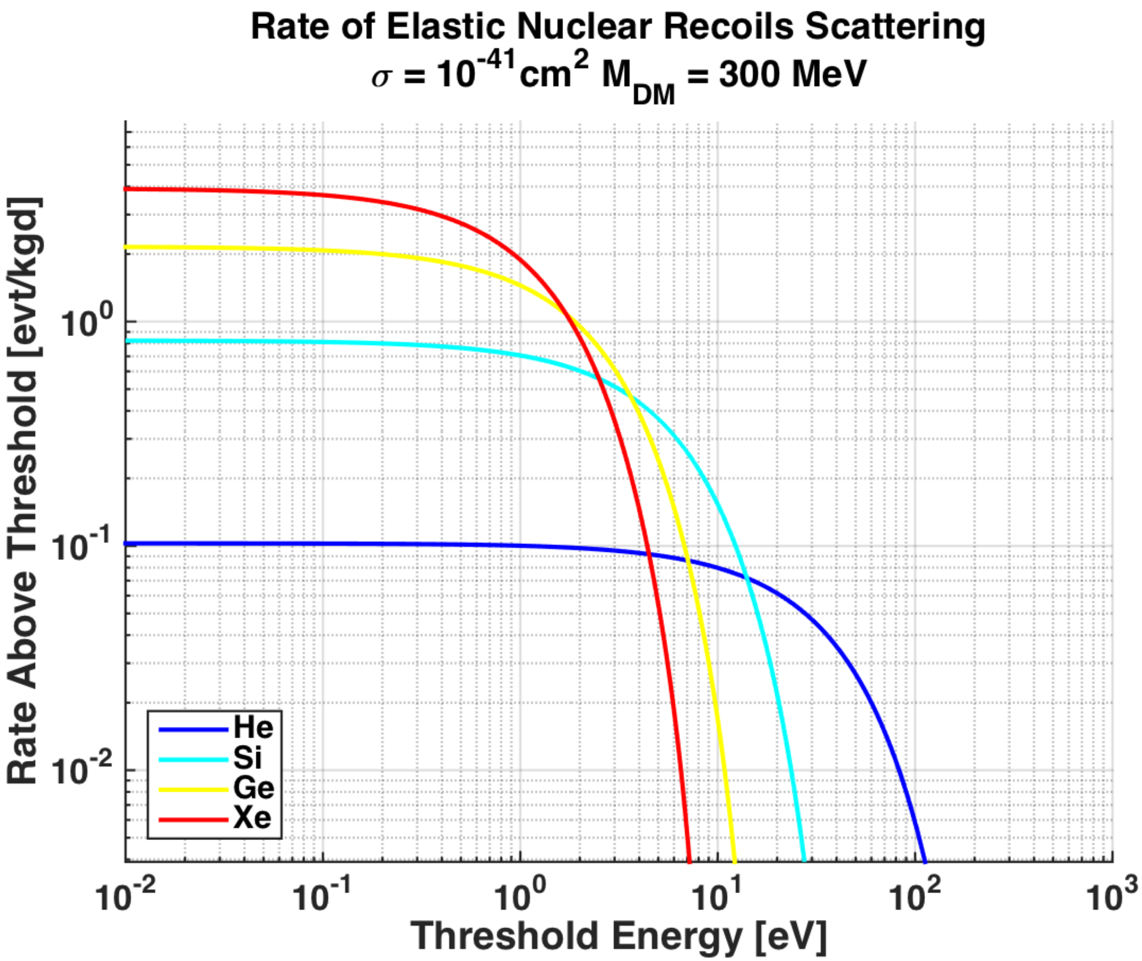
$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v_{DM}^2}{M_n}$$
$$\lesssim \frac{4M_{DM}}{M_n} E_{DM}$$

- Large nuclei have large coherent rate enhancement
- Transfer of DM kinetic energy inefficient when $M_n >> M_{DM}$ for elastic scatters



Dominant Design Driver: Energy Threshold

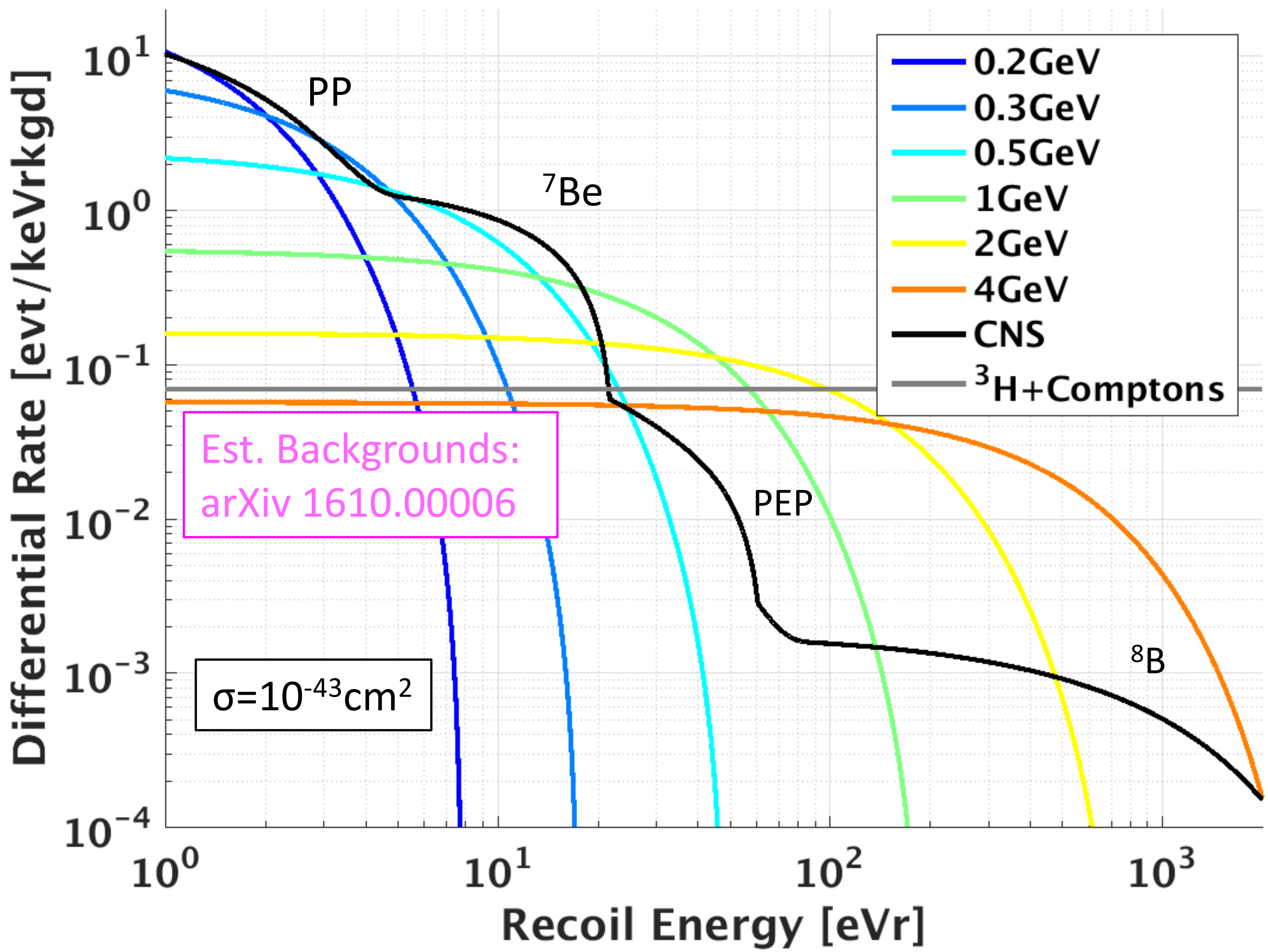
- Ge: larger signal rate with really small threshold requirements
- He: smaller signal rates with small threshold requirements



Design Goals: 300 MeV < M_{DM} <6 GeV

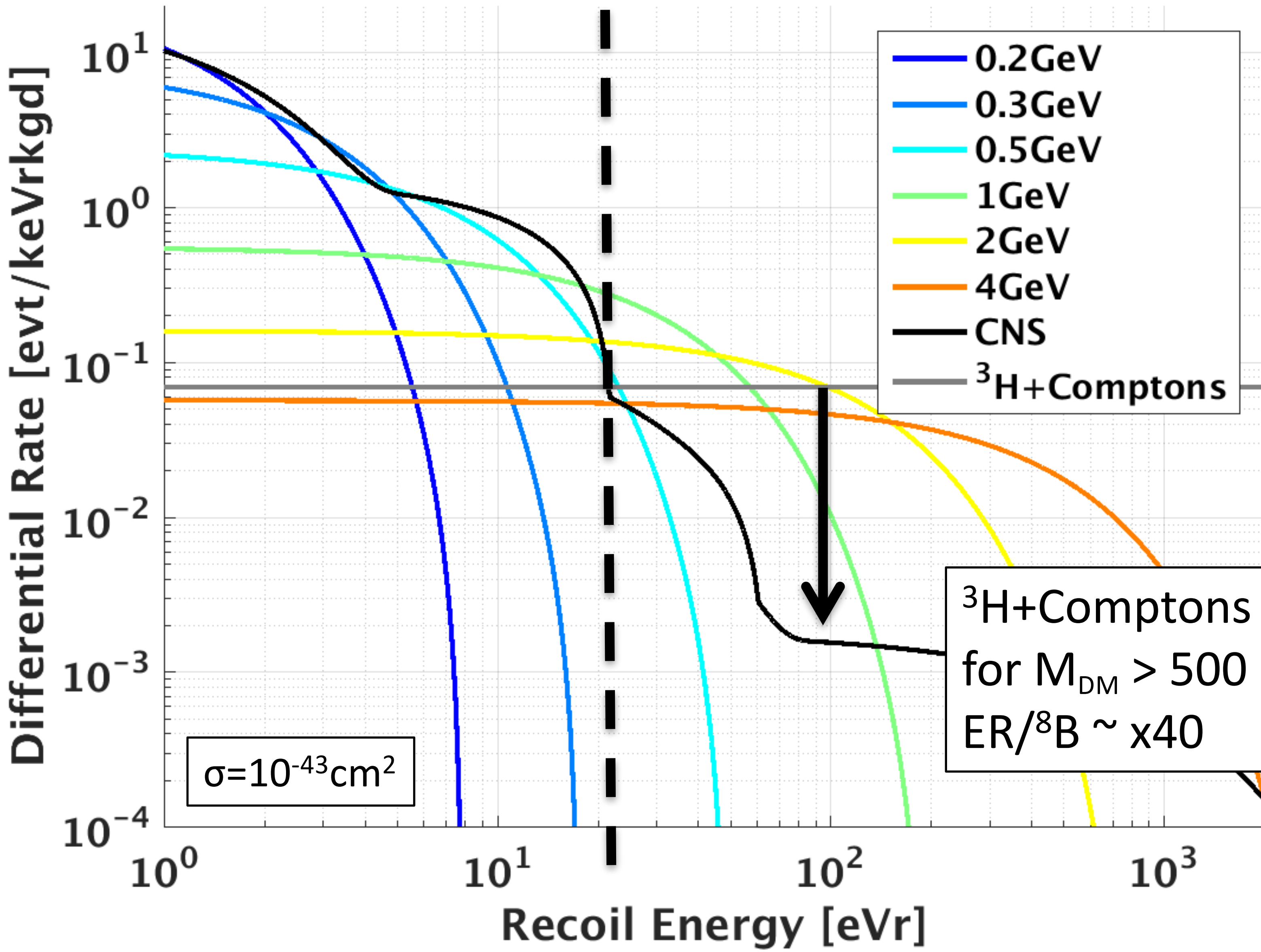
	Ge	He
Energy Threshold	~ 10 eV	~ 100 eV
Active Mass	10 kg	200kg

Ge: Rough Background Estimates at SNOLAB



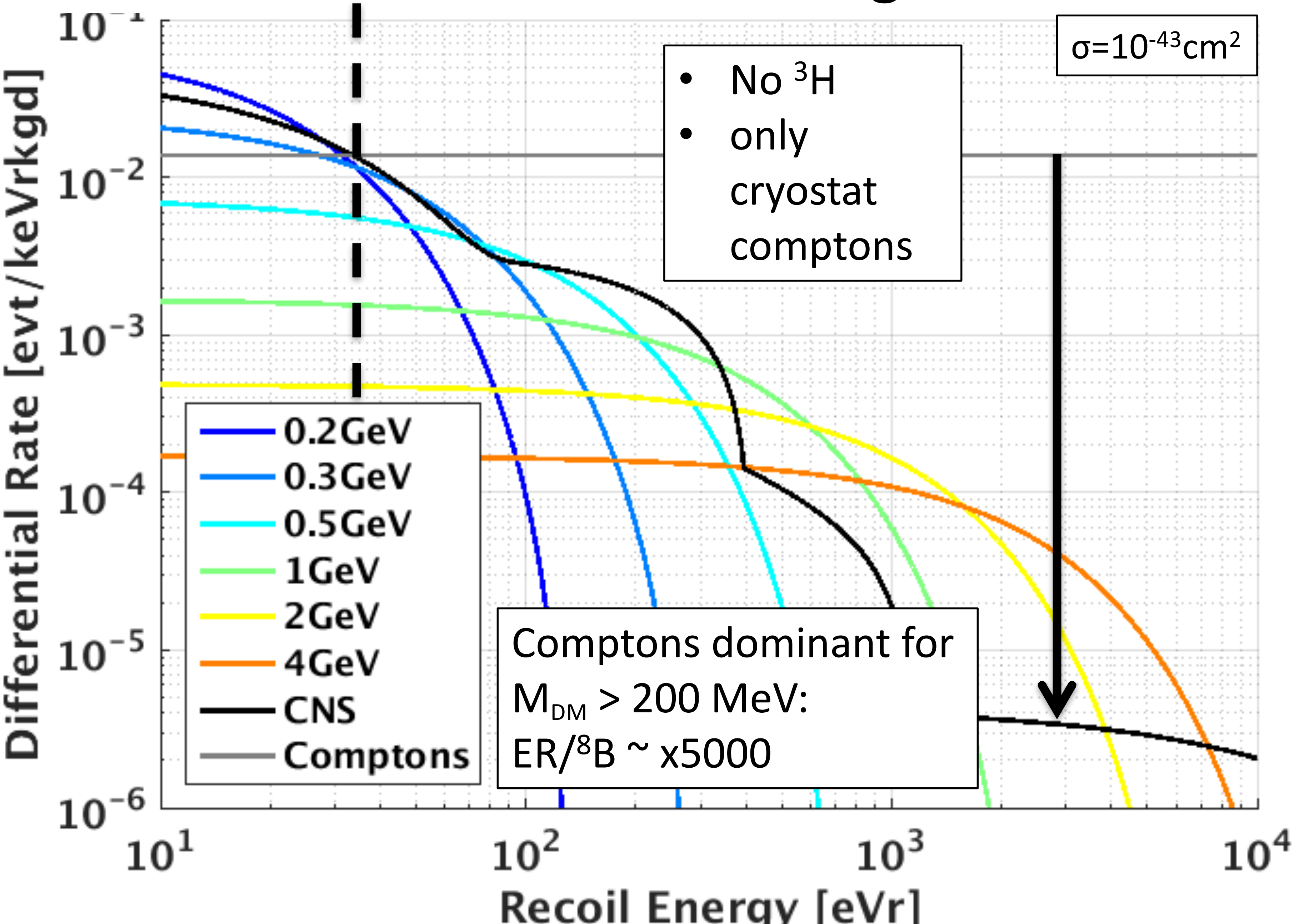
Smaller DM masses have less overlap with flat backgrounds!

Ge: Rough Background Estimates at SNOLAB



^{3}H+Comptons dominant for M_{DM} > 500 MeV: ER/^{8}B ~ x40

He: SNOLAB Level Backgrounds



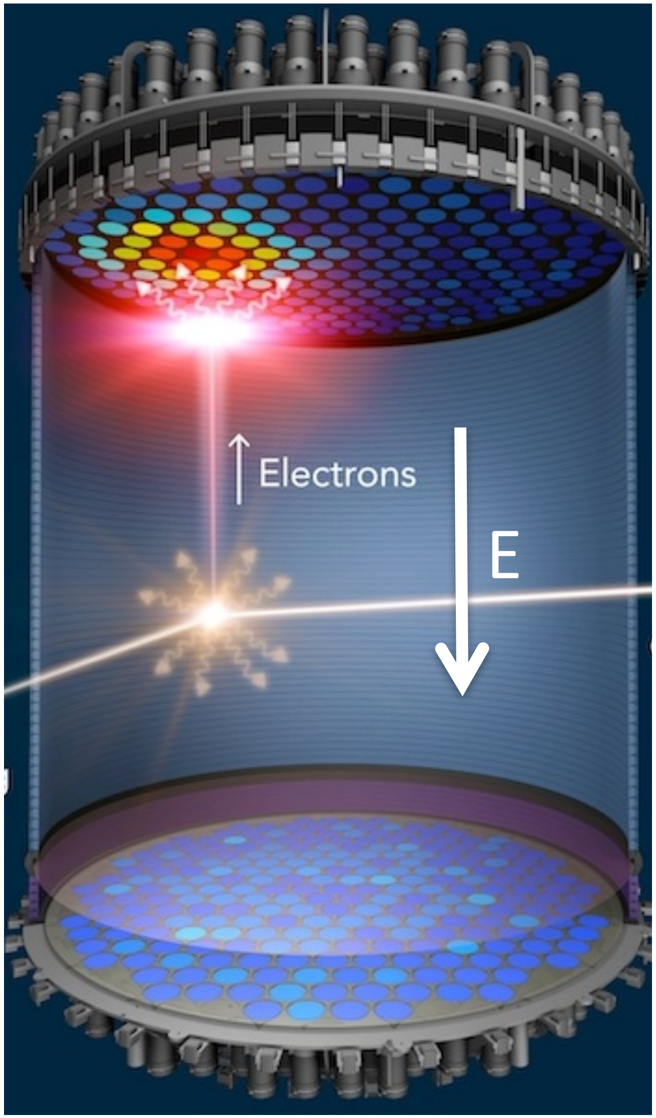
Design Goals: 300 MeV < M_{DM} <6 GeV

	Ge	He
NR Energy Threshold	~ 10 eV	~ 100 eV
Active Mass	10 kg	100 kg
ER/NR Discrimination	~ x40 (arXiv 1610.00006)	~ x5000

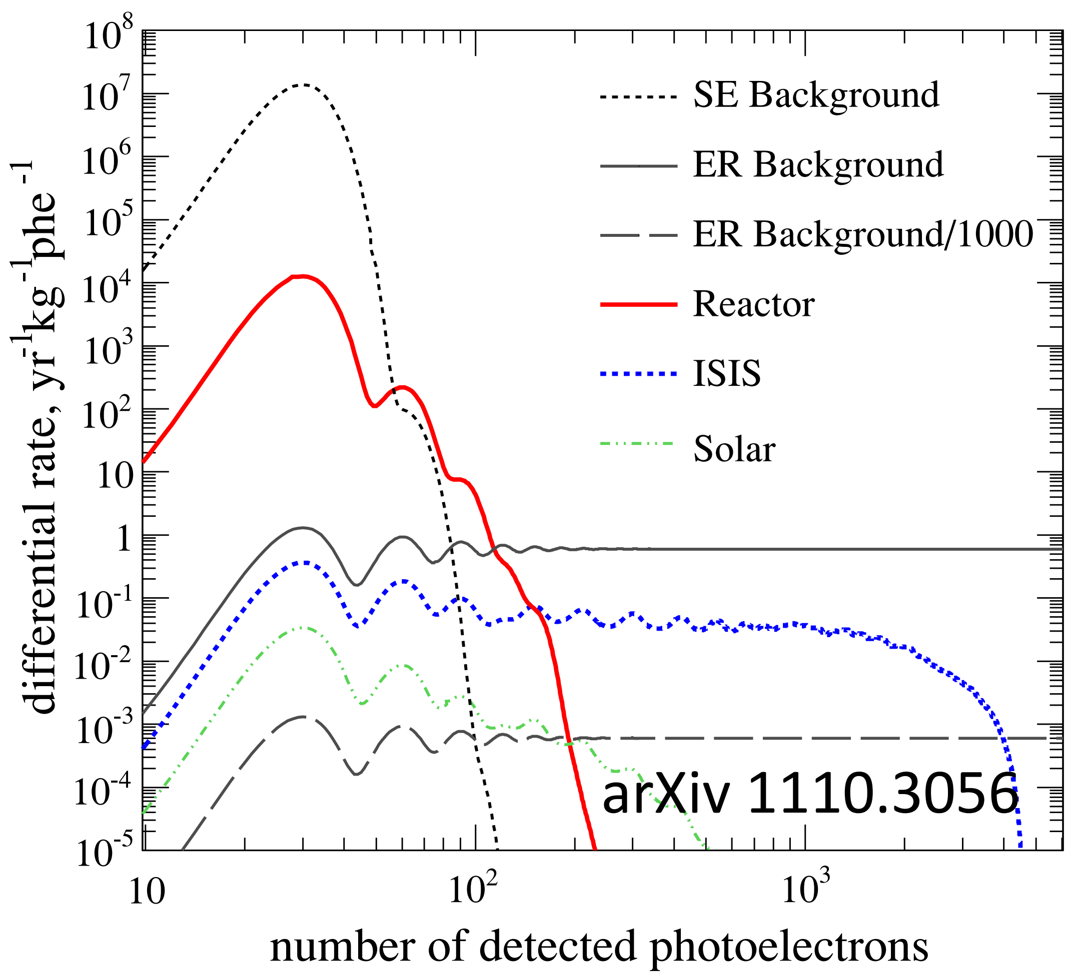
These numbers a bit handwavy

- LN Gain -> Different dR/dEr -> dR/d? stretching
- Depends upon radiopurity …

Problem 3: Dark Counts



e^- (S2) Background Rate in Zeplin III



R_{1e-} = 5.7 Hz -> YIKES!

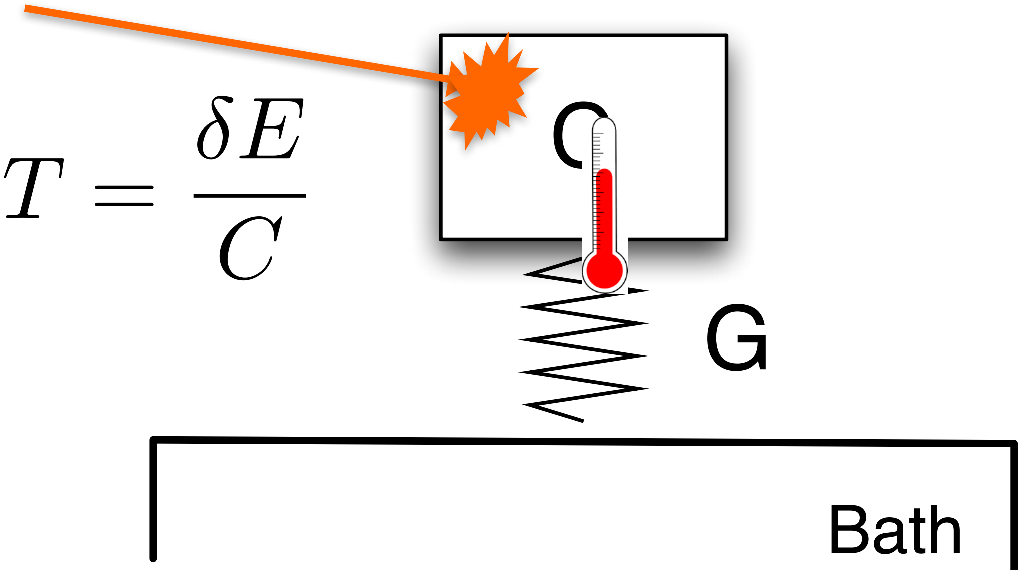
Design Goals: 300 MeV < M_{DM} <6 GeV

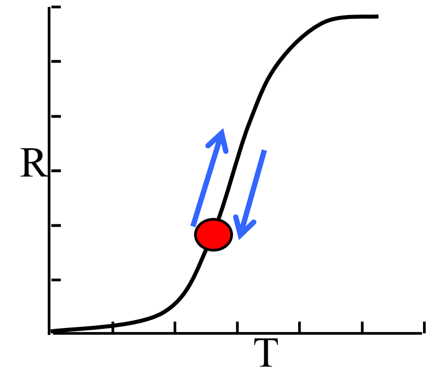
	Ge	He
NR Energy Threshold	~ 10 eV	~ 100 eV
Active Mass	10 kg	100 kg
ER/NR Discrimination	~ x40	~ x5000
No Dark Counts		

SuperCDMS

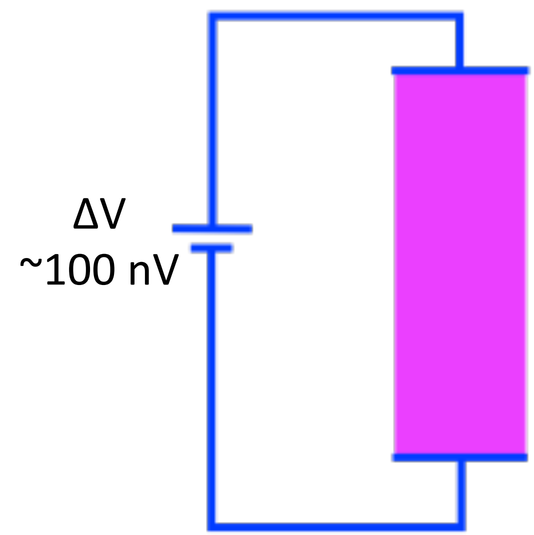
Low Temperature Calorimeter Technology

$$\delta T = \frac{\delta E}{C}$$





- Transition Edge Sensor (TES):
  A superconducting metal film (W) that is externally biased so as to be within its superconducting/normal transition
- **“Near Equilibrium Sensor”: No Dark Count Rate**

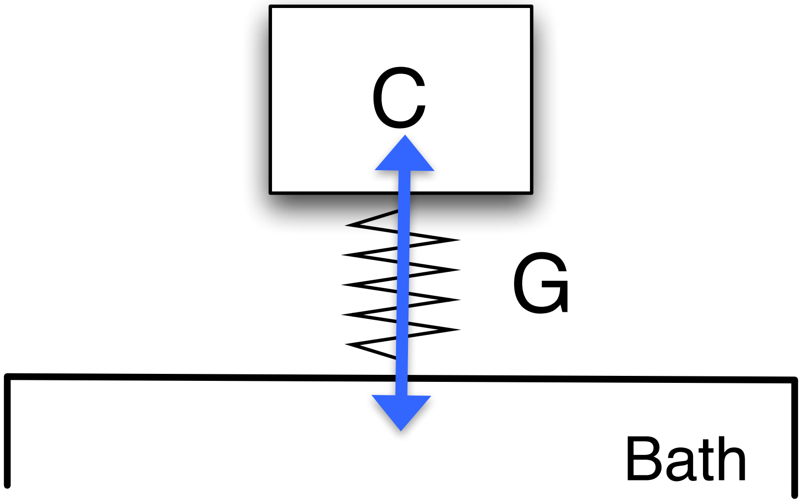


Calorimeter Sensitivity

$$\sigma^2_{<E>} = \sum_i (E_i - <E>)^2 \frac{e^{-\beta E_i}}{\sum_j e^{-\beta E_j}}$$

$$= \frac{\sum_i E_i^2 e^{-\beta E_i}}{\sum_j e^{-\beta E_j}} - <E>^2$$

$$= -\frac{\partial <E>}{\partial \beta} = \frac{\partial <E>}{\partial T} k_b T^2 = C k_b T^2$$



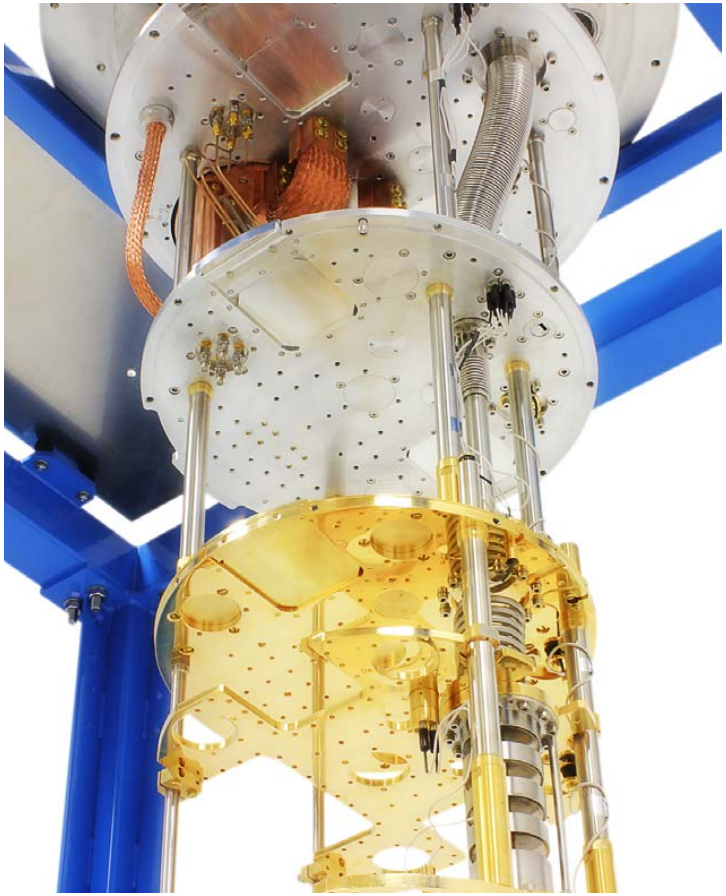
~ Intrinsic Thermal Noise of Calorimeters

Calorimeter Optimization

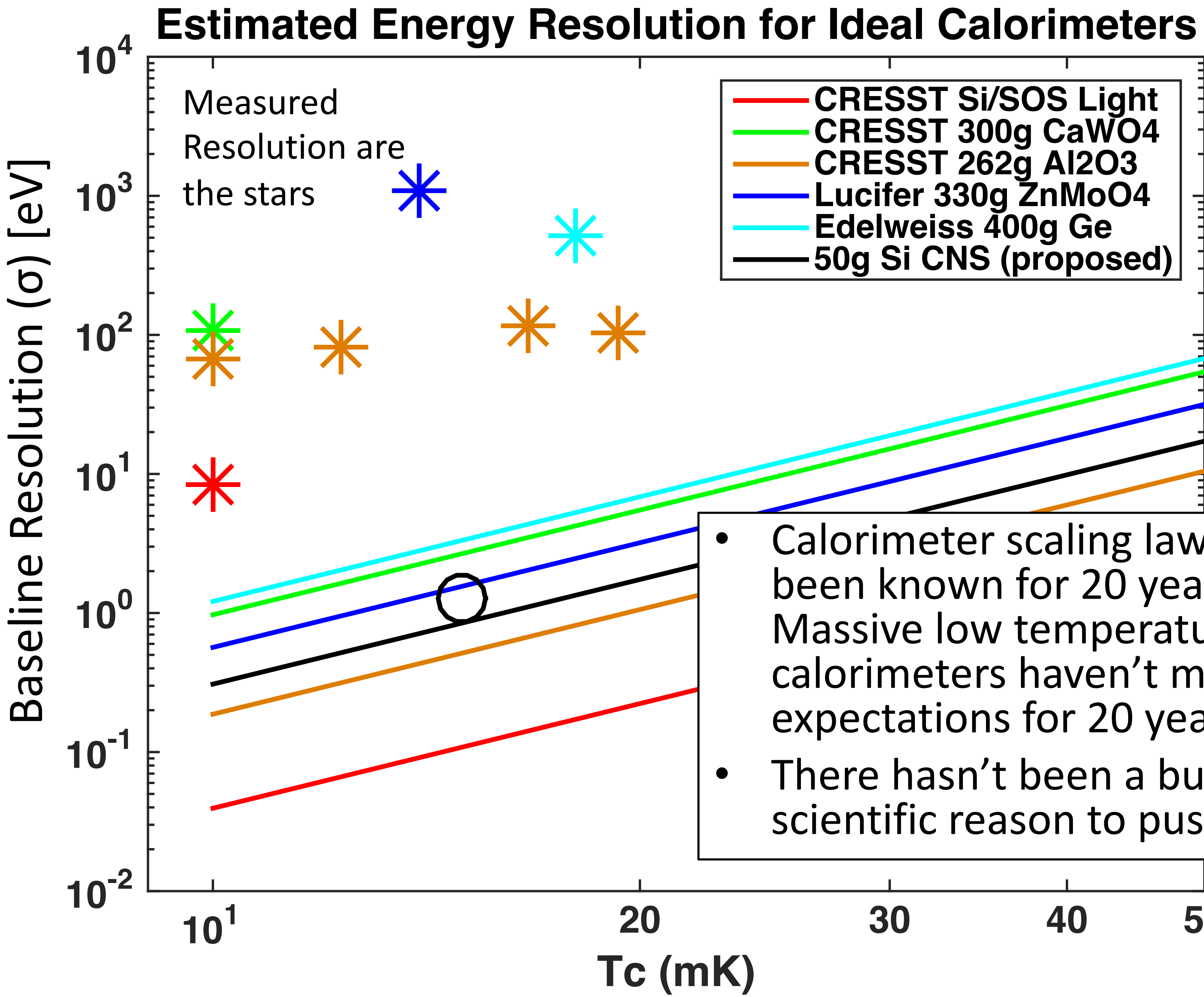
$$\sigma^2_{<E>} = C k_b T^2$$

- Minimize T
  - Dilution Refrigerators can cool detectors to 5mK
- Minimize C
  - ~~Small Volume~~
  - Low T
  - Insulators

} Freeze out

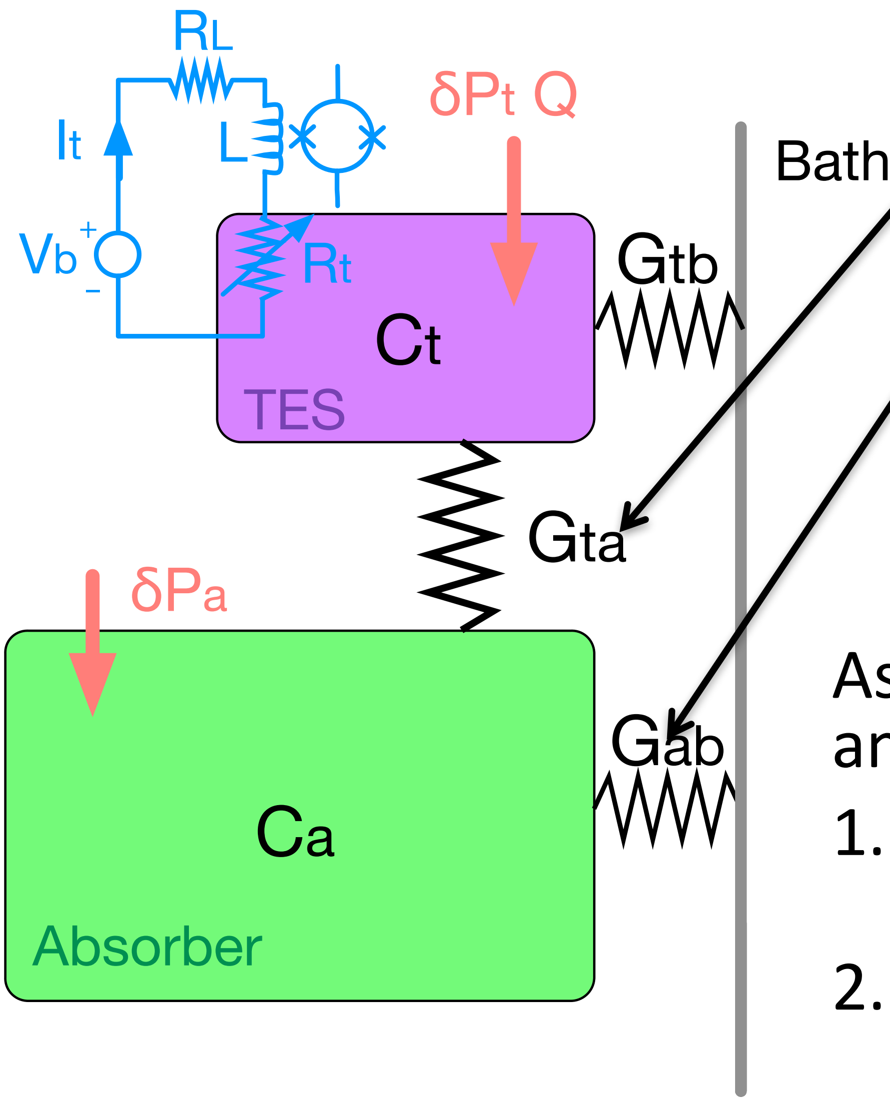


Shouldn't this be a solved problem?



- Calorimeter scaling laws have been known for 20 years … Massive low temperature calorimeters haven't met expectations for 20 years
- There hasn't been a burning scientific reason to push

Culprit: Decoupling between the Sensor and Absorber at Low Temperature



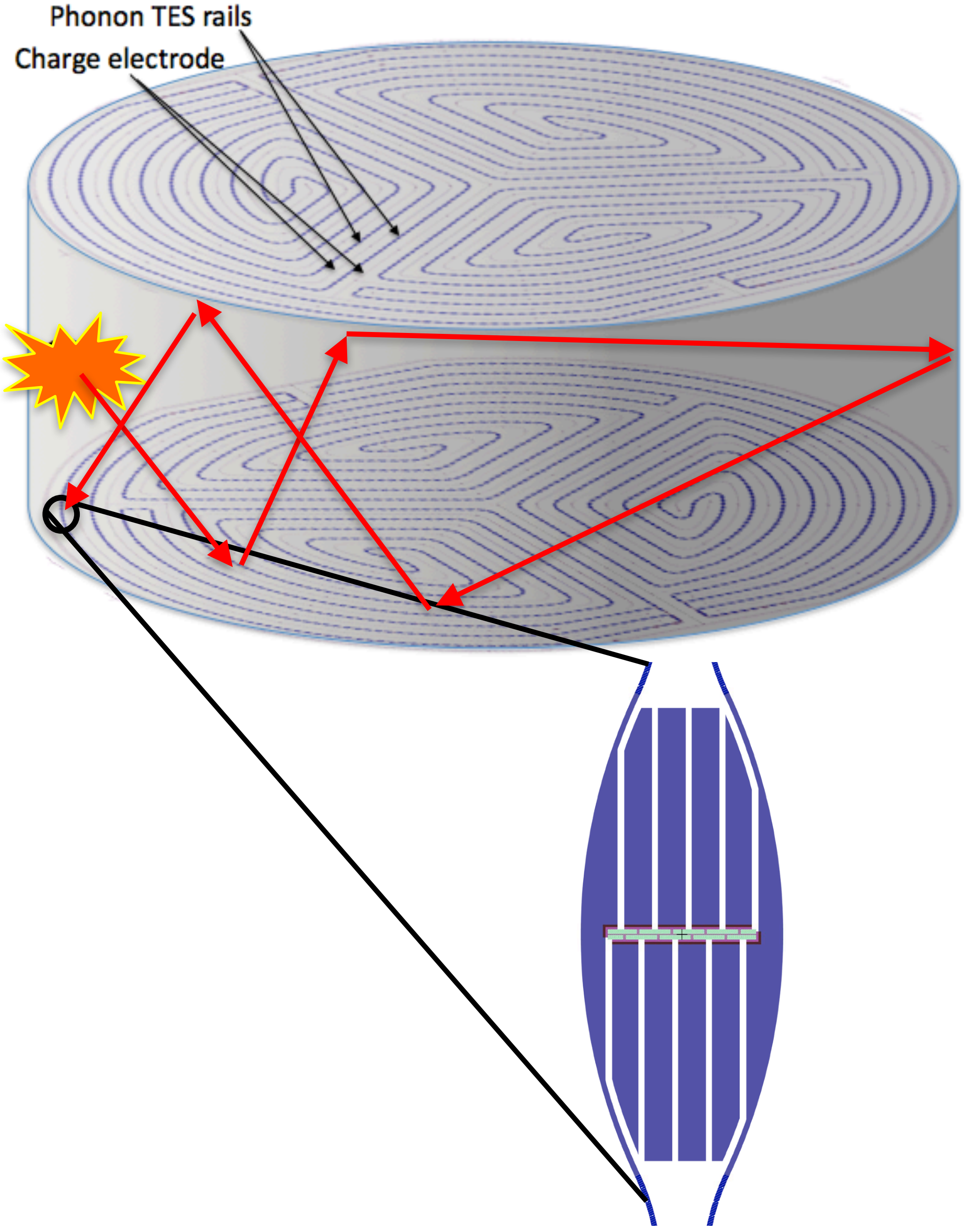
e⁻/phonon thermal conductance scales as T^4

Kapitza boundary conductance in the mechanical support scale as as T^3

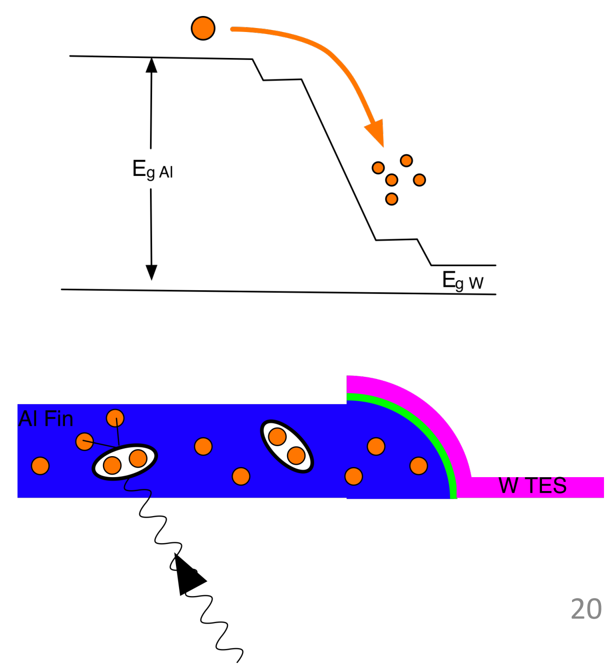
As T is decreased, it's harder and harder to keep the sensor:

1. the sensor thermally coupled to the absorber
2. The absorber and sensor decoupled from the bath

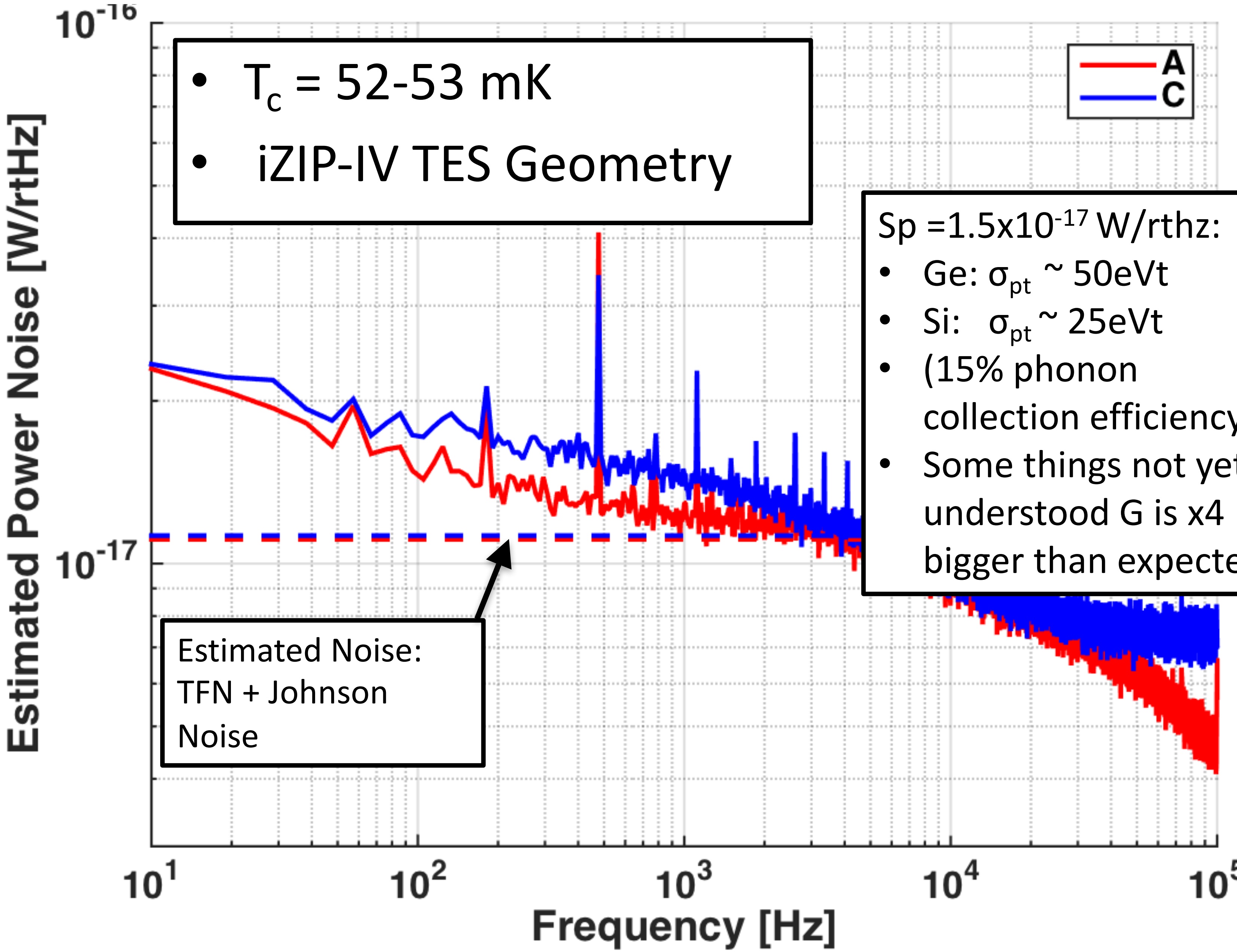
Solution: Athermal Phonon Sensors



Collect and concentrate athermal phonon energy into TES via Al QP collection fins, completely bypassing the G_{ep} bottleneck



Noise of G23R Test Device



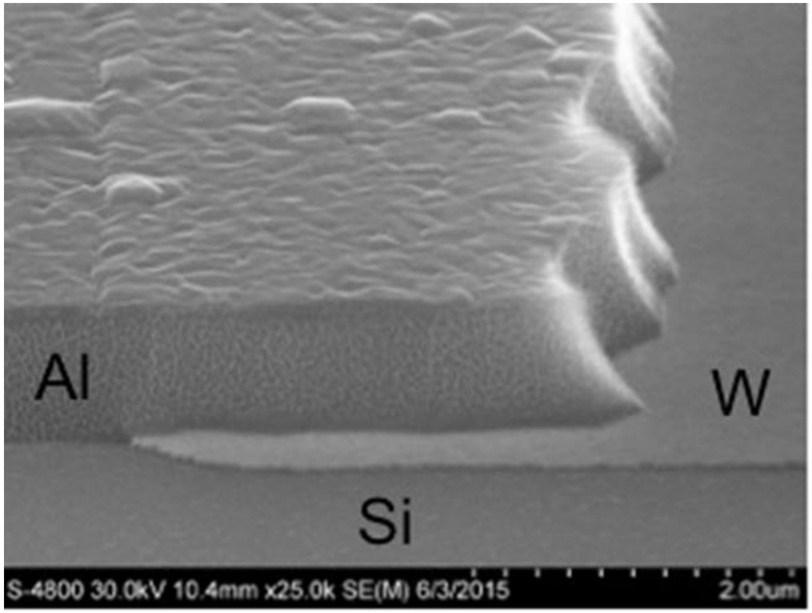
- T_c = 52-53 mK
- iZIP-IV TES Geometry

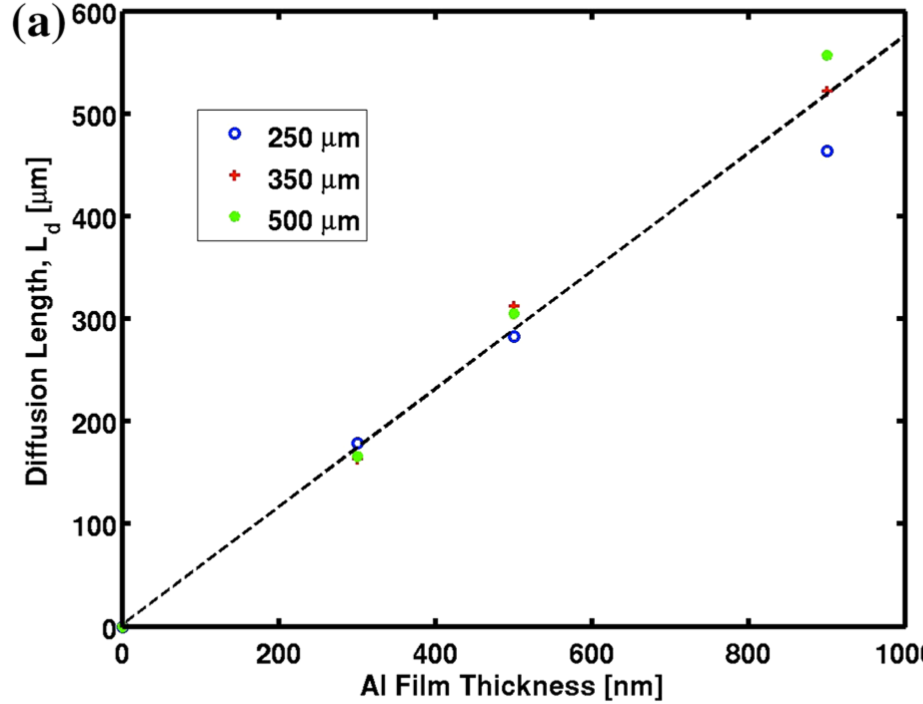
Sp =1.5x10^{-17} W/rthz:

- Ge: σ_{pt} ~ 50eVt
- Si: σ_{pt} ~ 25eVt
- (15% phonon collection efficiency)
- Some things not yet understood G is x4 bigger than expected

Estimated Noise: TFN + Johnson Noise

R&D:Optimizing the Phonon Sensor 1





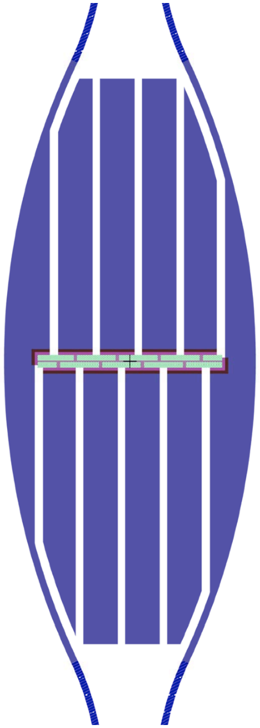
SuperCDMS Soudan: W TES above Al Fin

SuperCDMS SNOLAB: W TES below Al Fin

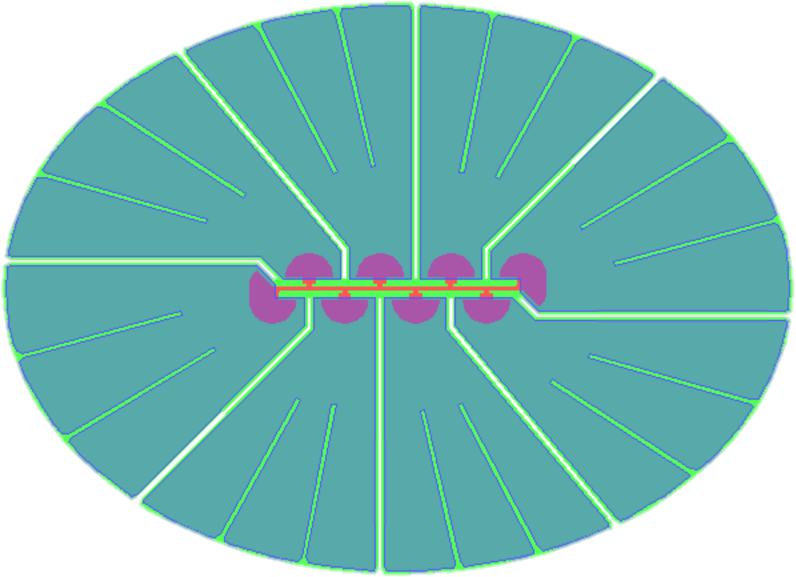
- Losses at every part of the phonon energy collection process must be minimized
- QP diffusion length scales linearly with Al thickness
- New Fabrication Process: W TES now below Al Fin
- 350 nm Al (Soudan) -> 900 nm Al (SNOLAB)
- Now limited by transmission at W/Al interface
- J. Yen et al, Low Temp Phys (2016) 184:30

R&D: Optimizing the Phonon Sensor 2

SuperCDMS Soudan

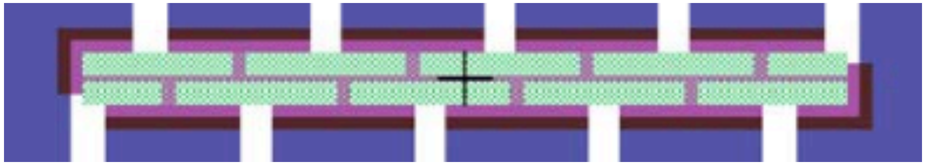


SuperCDMS SNOLAB

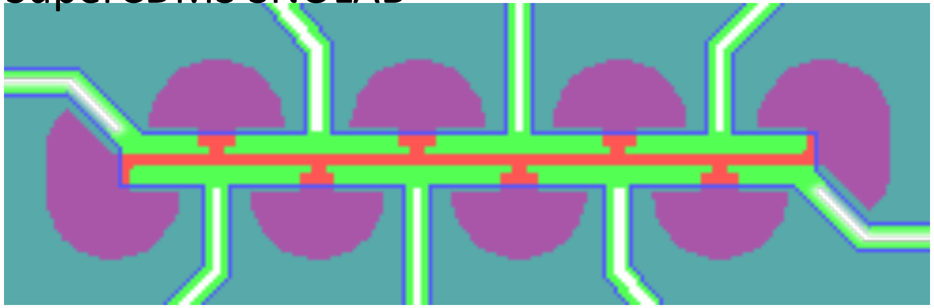


- TES noise scales with W volume but phonon collection bandwidth scales with Al fin area
- 2D Al Fin Geometries have more efficient collection than 1D geometries used in Soudan

SuperCDMS Soudan



SuperCDMS SNOLAB

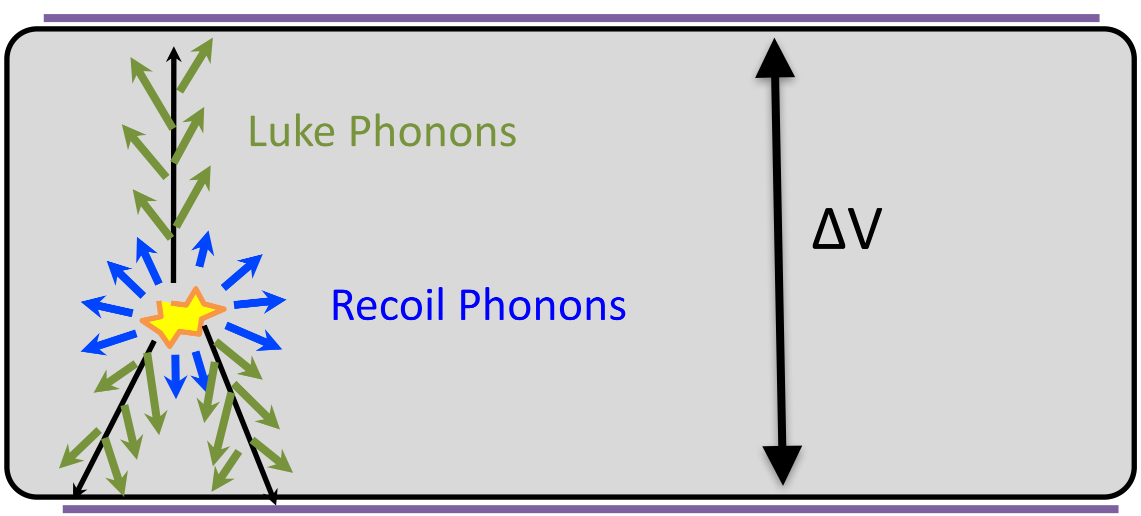


- Minimize W TES volume in the fin connector

Studies of SNOLAB HV phonon sensor ongoing now at UMN and Berkeley. Results preliminary but very promising!

Luke-Neganov Phonon Production

- Drifting charges release kinetic energy via Luke-Neganov Phonon Production
- $$\begin{aligned} E_{total} &= E_{recoil} + E_{luke} \\ &= E_{recoil} + Qe\Delta V \end{aligned}$$

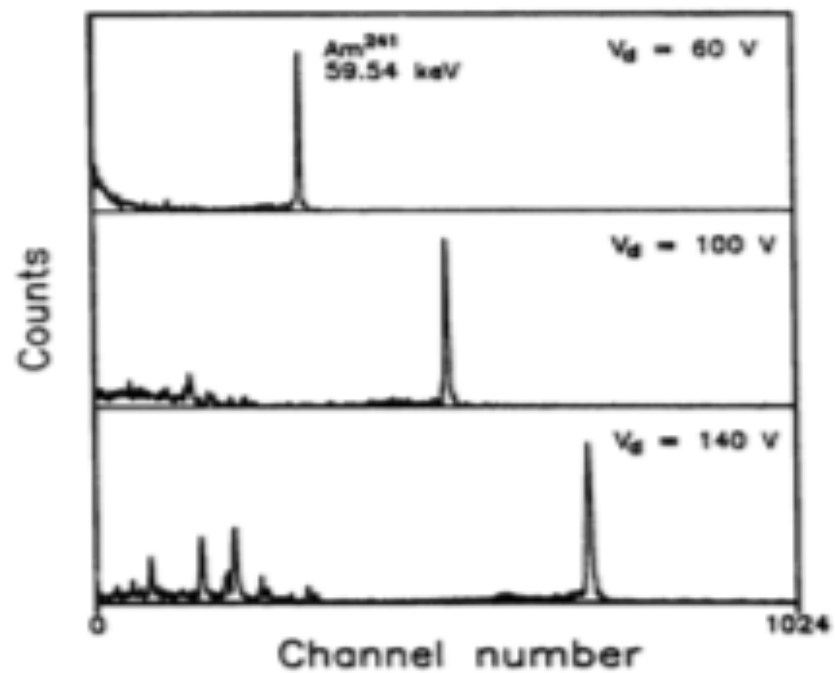


Luke-Neganov Ionization Amplification

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + Qe\Delta V$$

$$\lim_{\Delta V \to \infty} E_{total} \propto Q$$

At high voltage you've made an ionization amplifier

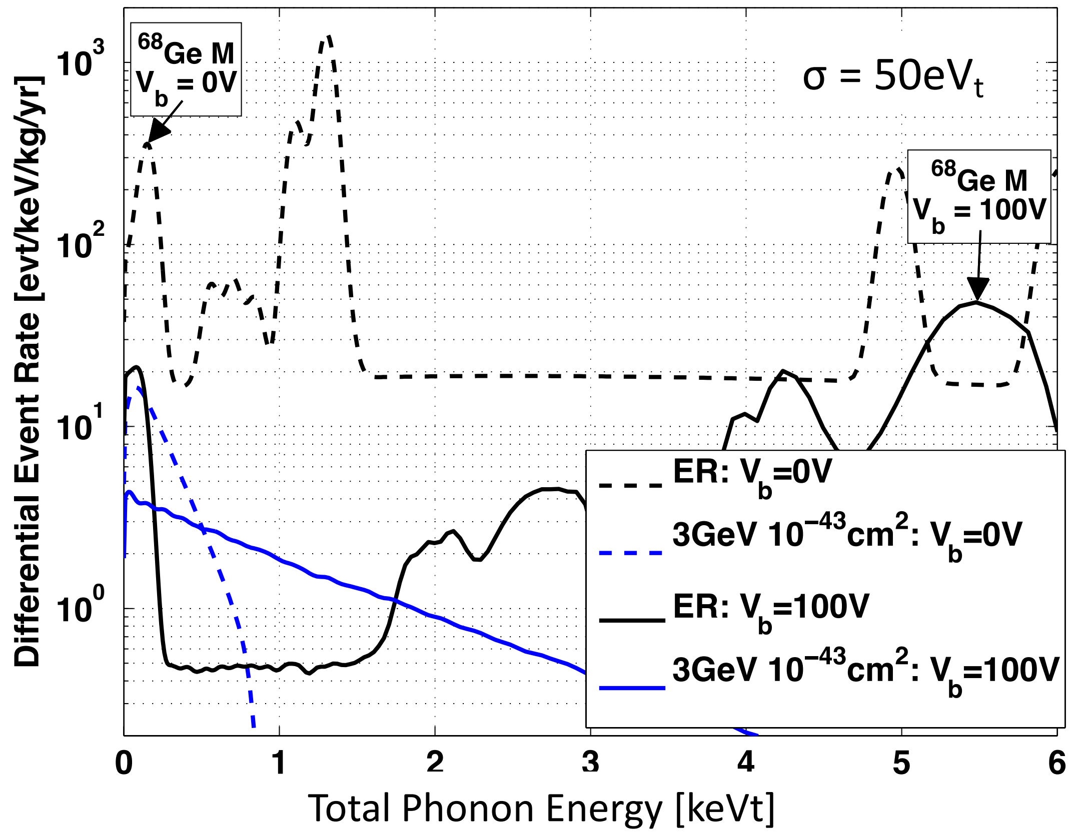


P.N. Luke et al. NIM A289, 405 (1990)

Preferential Stretching of Electronic Recoils

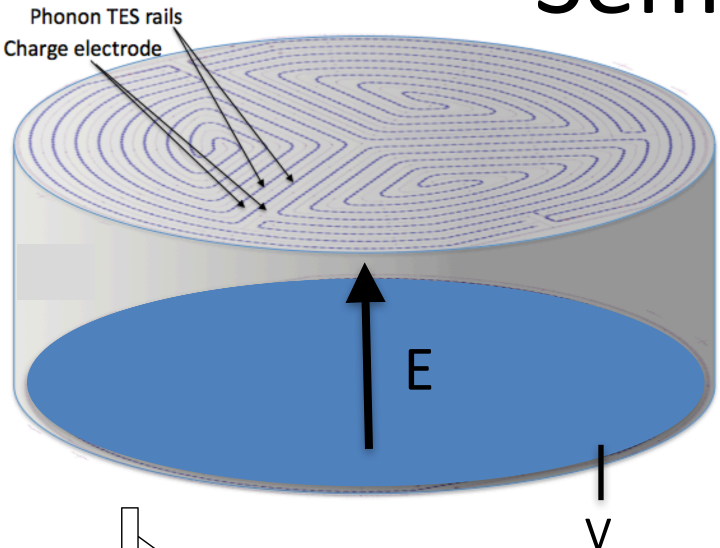
$$\begin{aligned} E_{total} &= E_{recoil} + E_{luke} \\ &= E_{recoil} + Qe\Delta V \\ &= E_{recoil}\left(1 + \frac{Ye\Delta V}{< E_{eh} >}\right) \end{aligned}$$

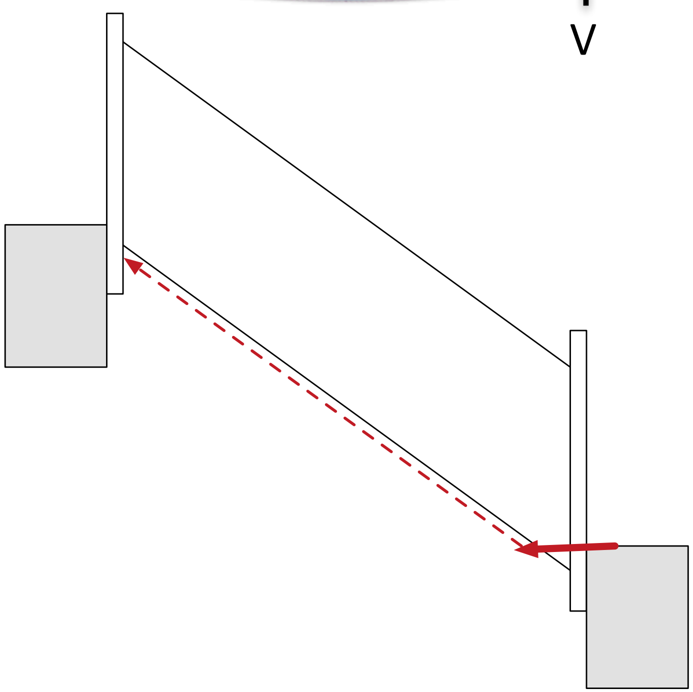
Since Electronic Recoils (ER) have larger Ionization Yields than Nuclear Recoils (NR), they have larger Luke Neganov Gain

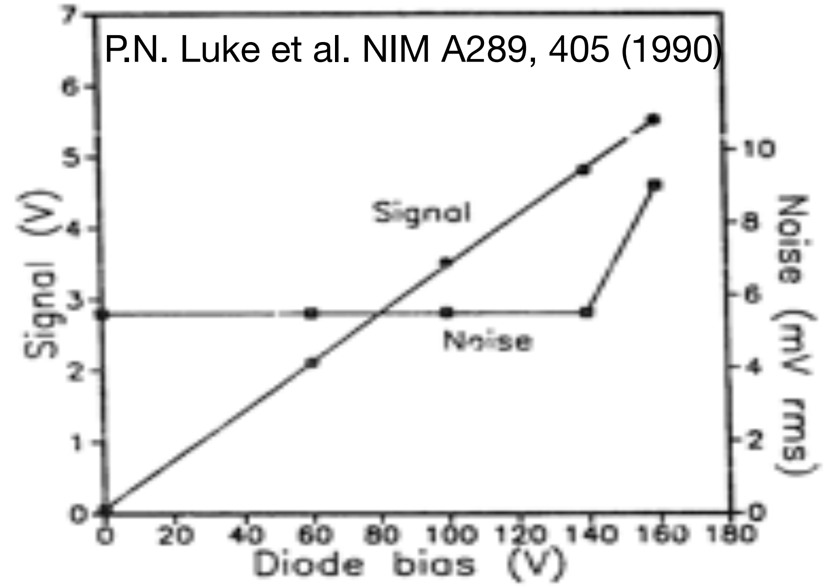


If you have phonon sensitivity to spare, this is tantamount to ER/NR Discrimination

Dark Current Leakage in Biased Semiconductors



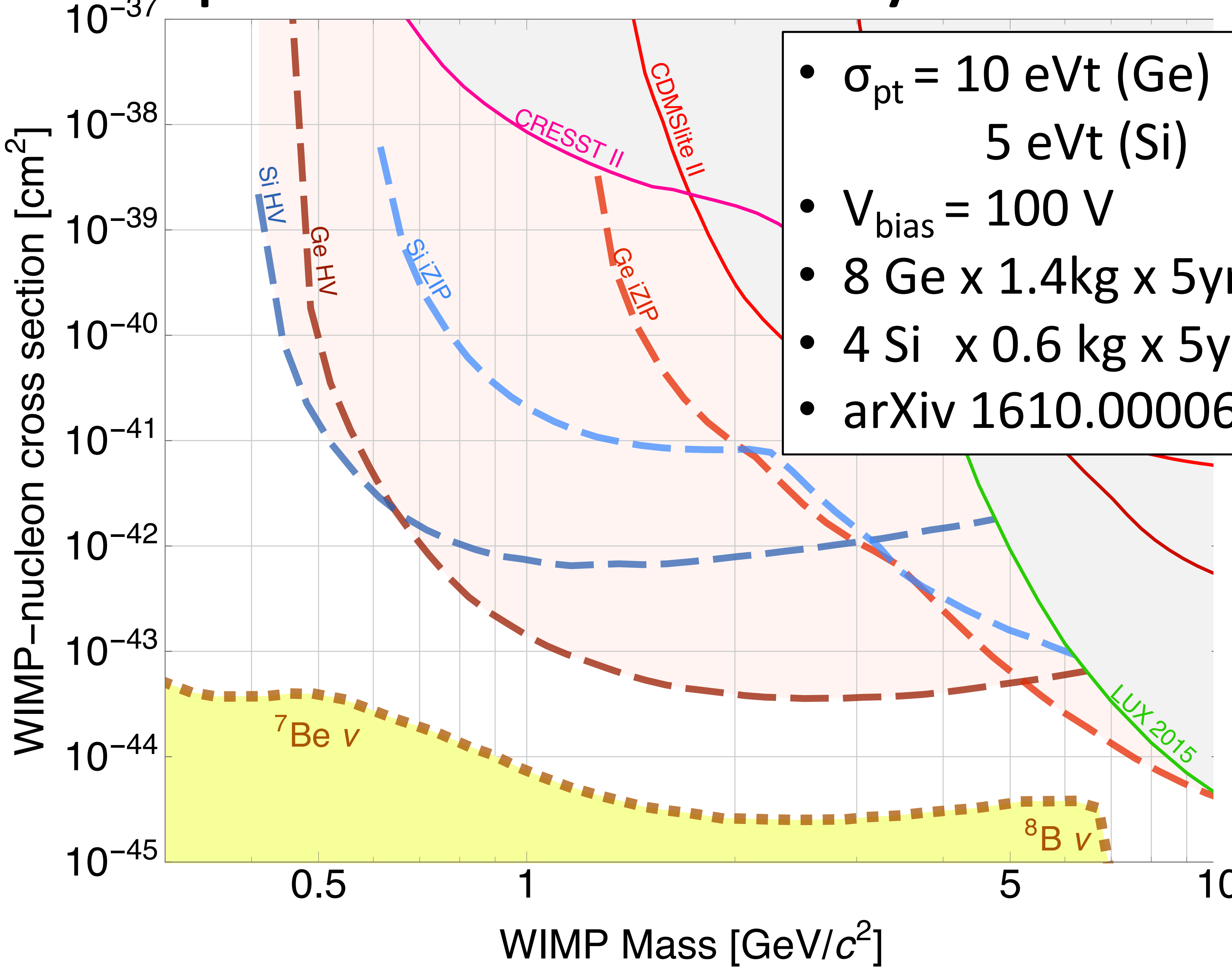




Man vs Nature

- Precision engineering required to have large E-fields and no leakage

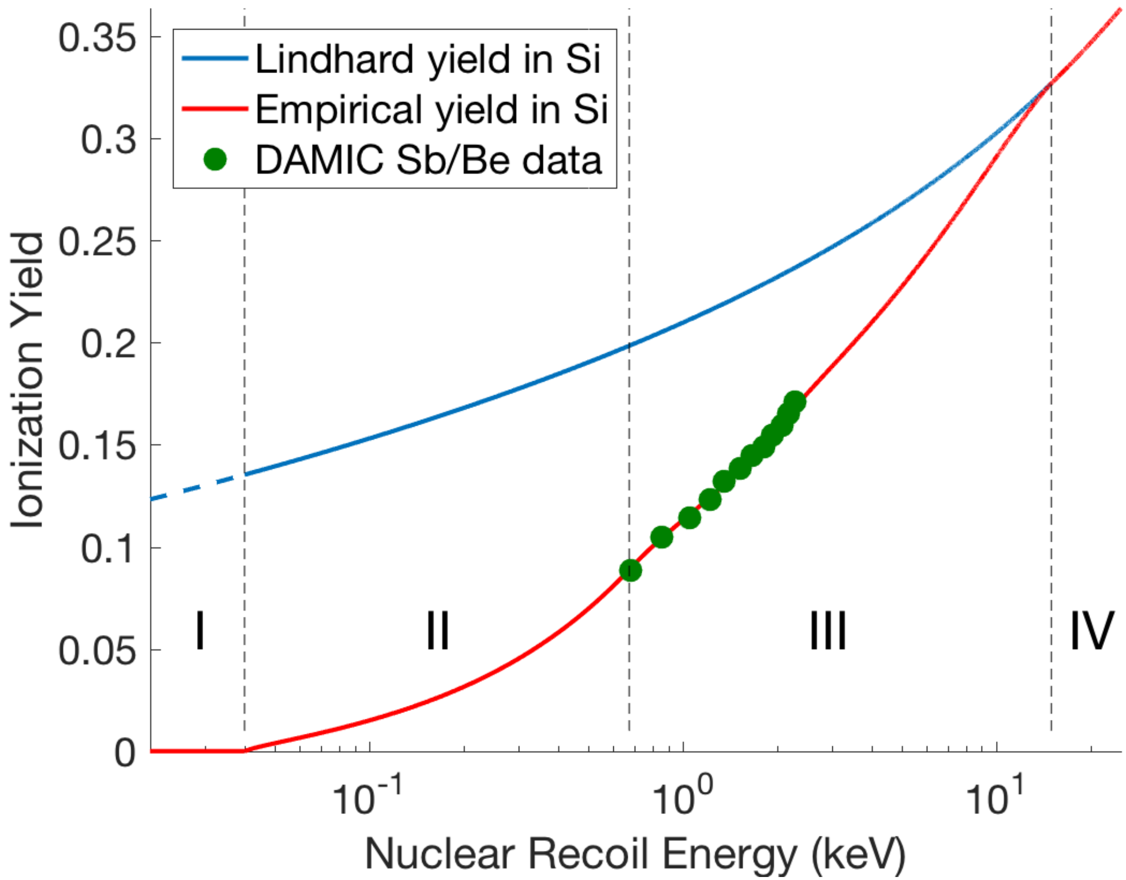
SuperCDMS Sensitivity Estimates



- σ_{pt} = 10 eVt (Ge)
  5 eVt (Si)
- V_{bias} = 100 V
- 8 Ge x 1.4kg x 5yr x 80%
- 4 Si x 0.6 kg x 5yr x 80%
- arXiv 1610.00006

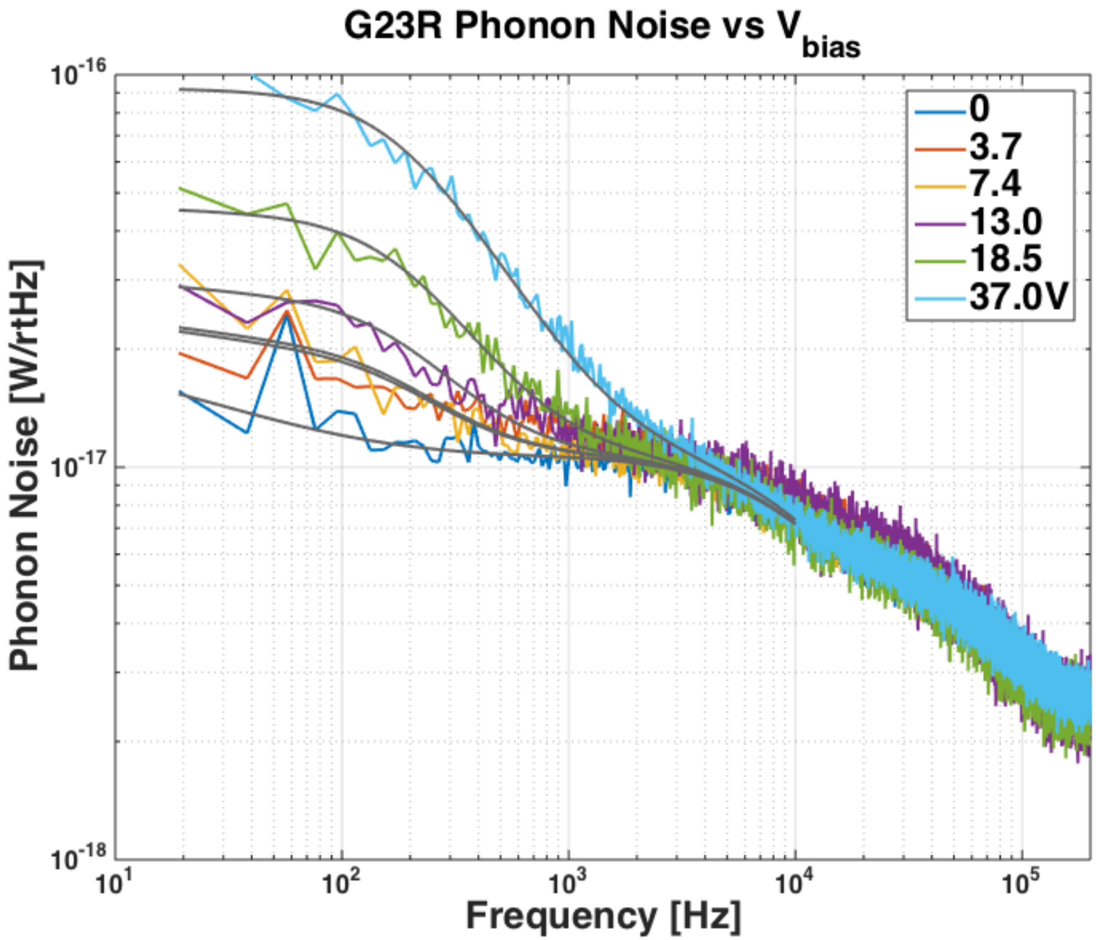
LN Gain: Sensitivity to Ionization Yield ?

- Ionization production for very small nuclear recoils unknown:
  Ge: Er > 254 eV
  Si: Er > 675 eV (DAMIC)
- Will measure as part of SuperCDMS Operations
- How sensitive are estimated SuperCDMS sensitivity curves to assumptions in ionization production?



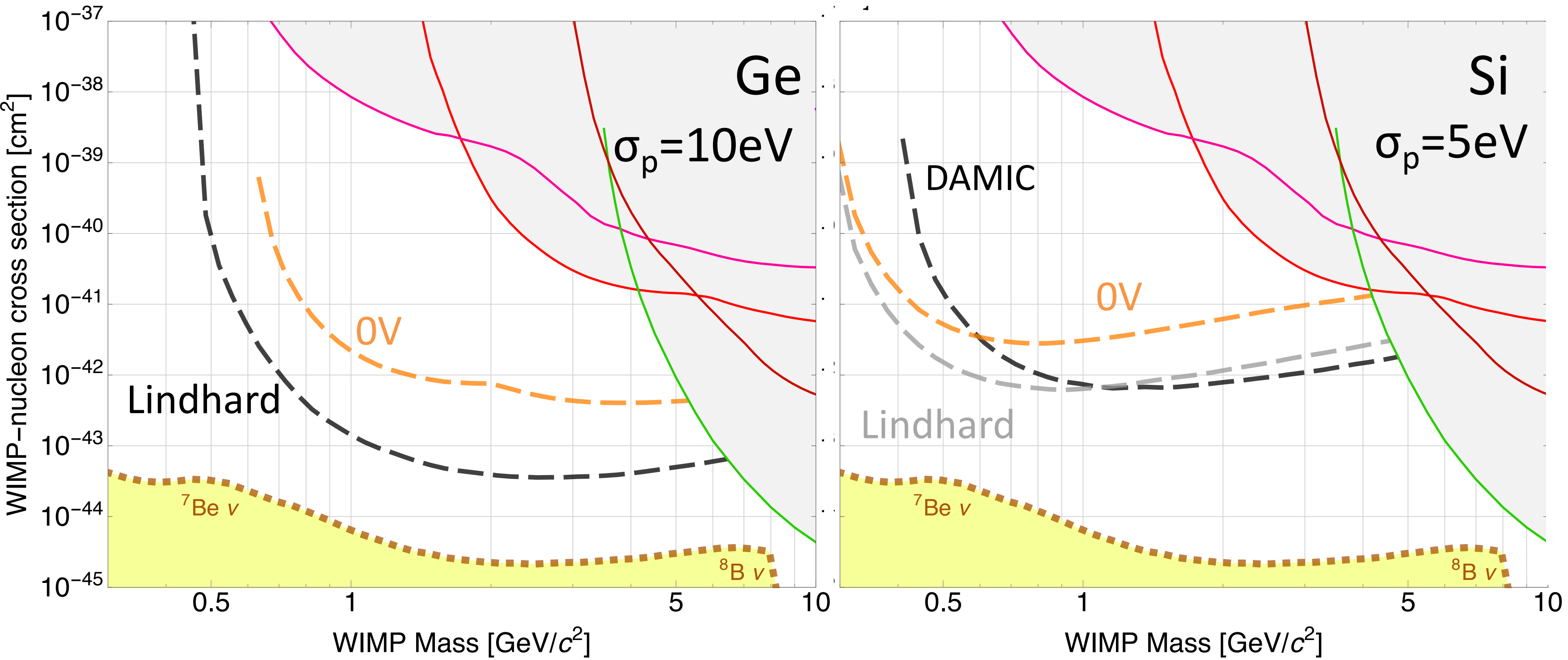
Let's conservatively bound this systematic uncertainty by looking at sensitivity curves with no Luke-Neganov Gain (with the detectors at 0V)

Sensitivity to Dark Current?



Let’s conservatively bound this systematic uncertainty by looking at sensitivity curves with no Luke-Neganov Gain (with the detectors at 0V)

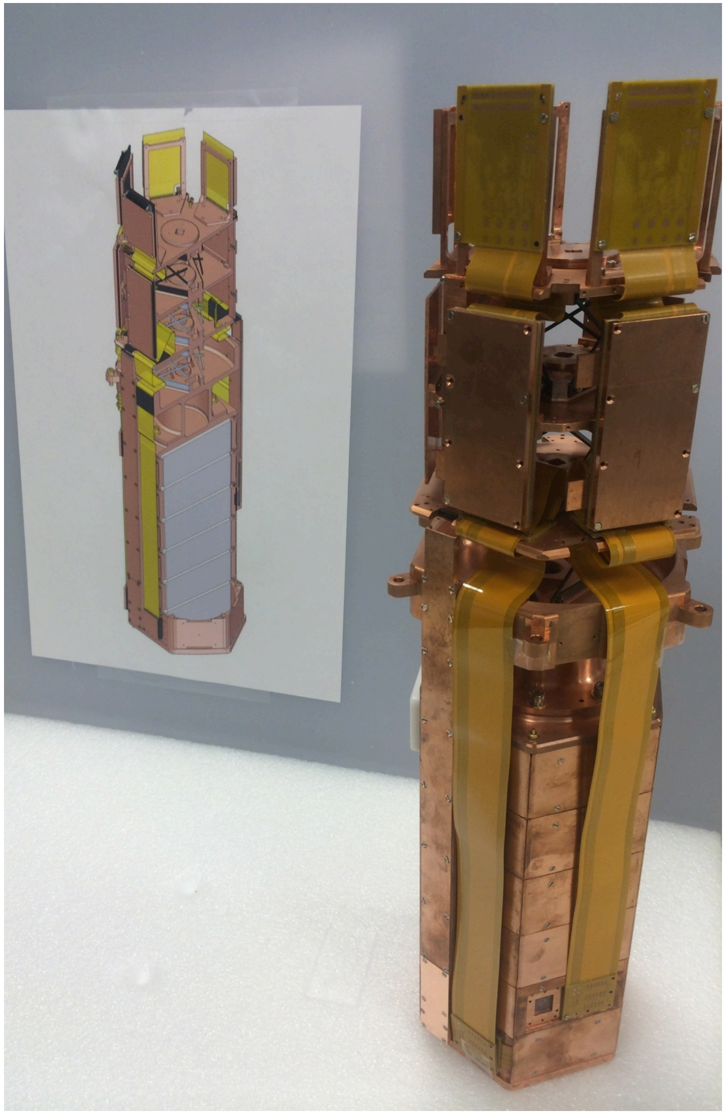
0V vs 100V Sensitivity Curves

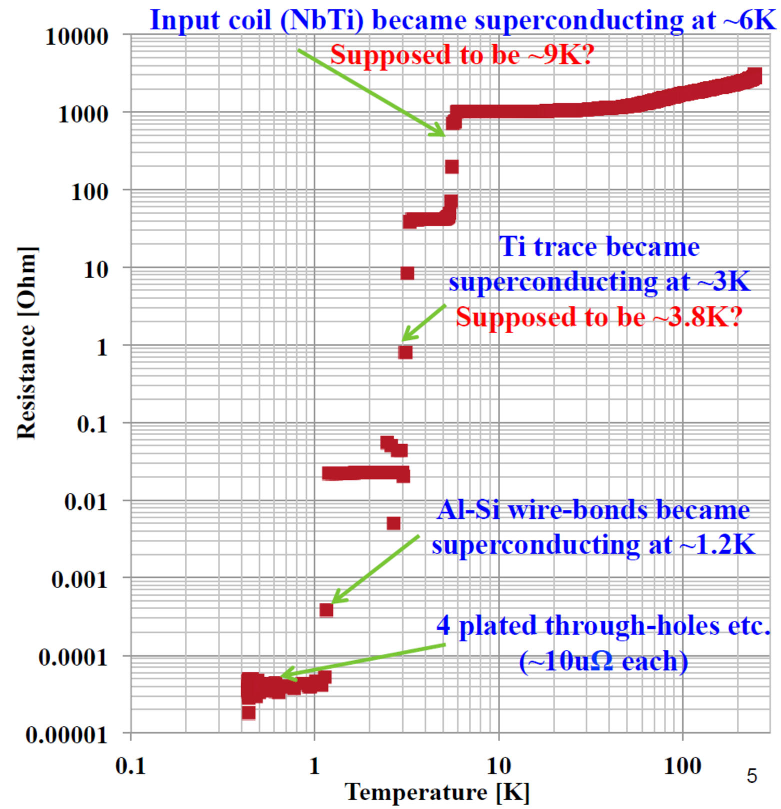


- Suppressed Sensitivity at higher masses: no preferential stretching of ER
- Si: Low mass sensitivity improvement because charge leakage cut is unnecessary
- 1610.00006

R&D Progress: Electronics/Support

Focus of this talk on the HV detector, but lots of other R&D has been successfully completed

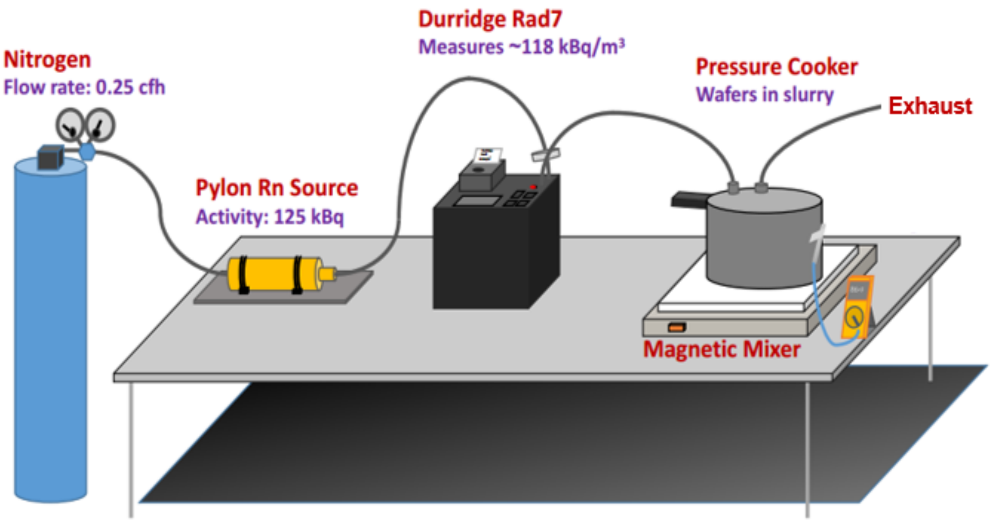




- Tower design finalized
- SQUID design finalized and tested
- Phonon cabling (in progress)

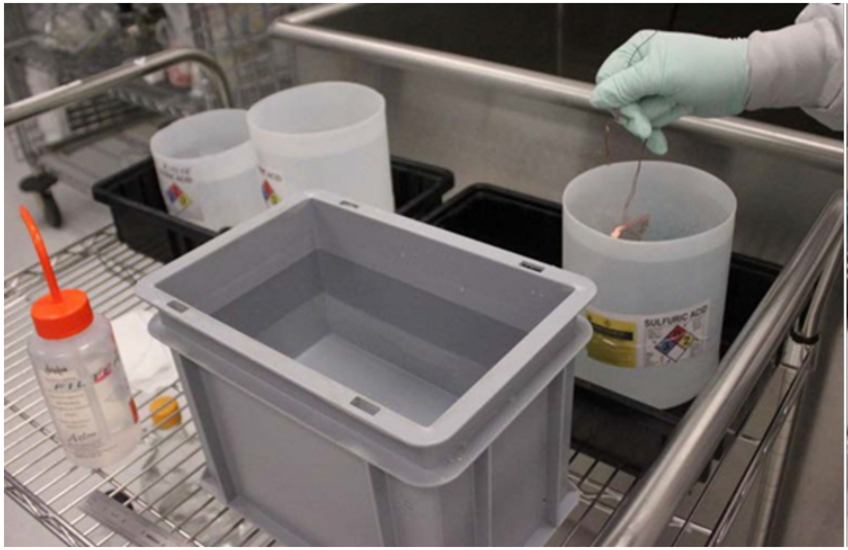
R&D Progress: Backgrounds

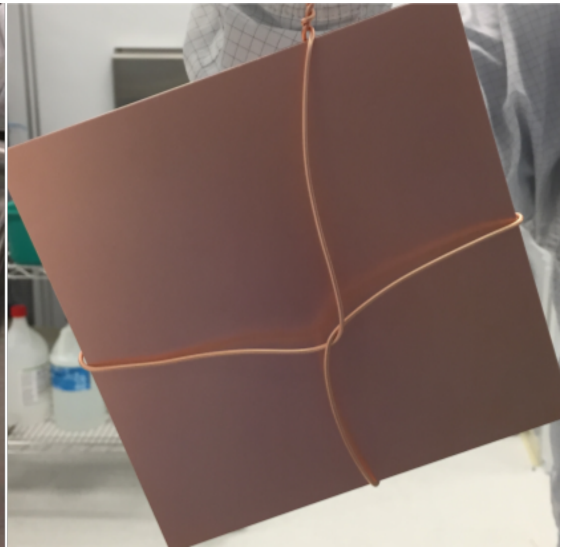
Focus of this talk on the HV detector, but lots of other R&D has been successfully completed



^{210}Pb Background Studies:

- On Detector (complete)
- On Cu (in progress)



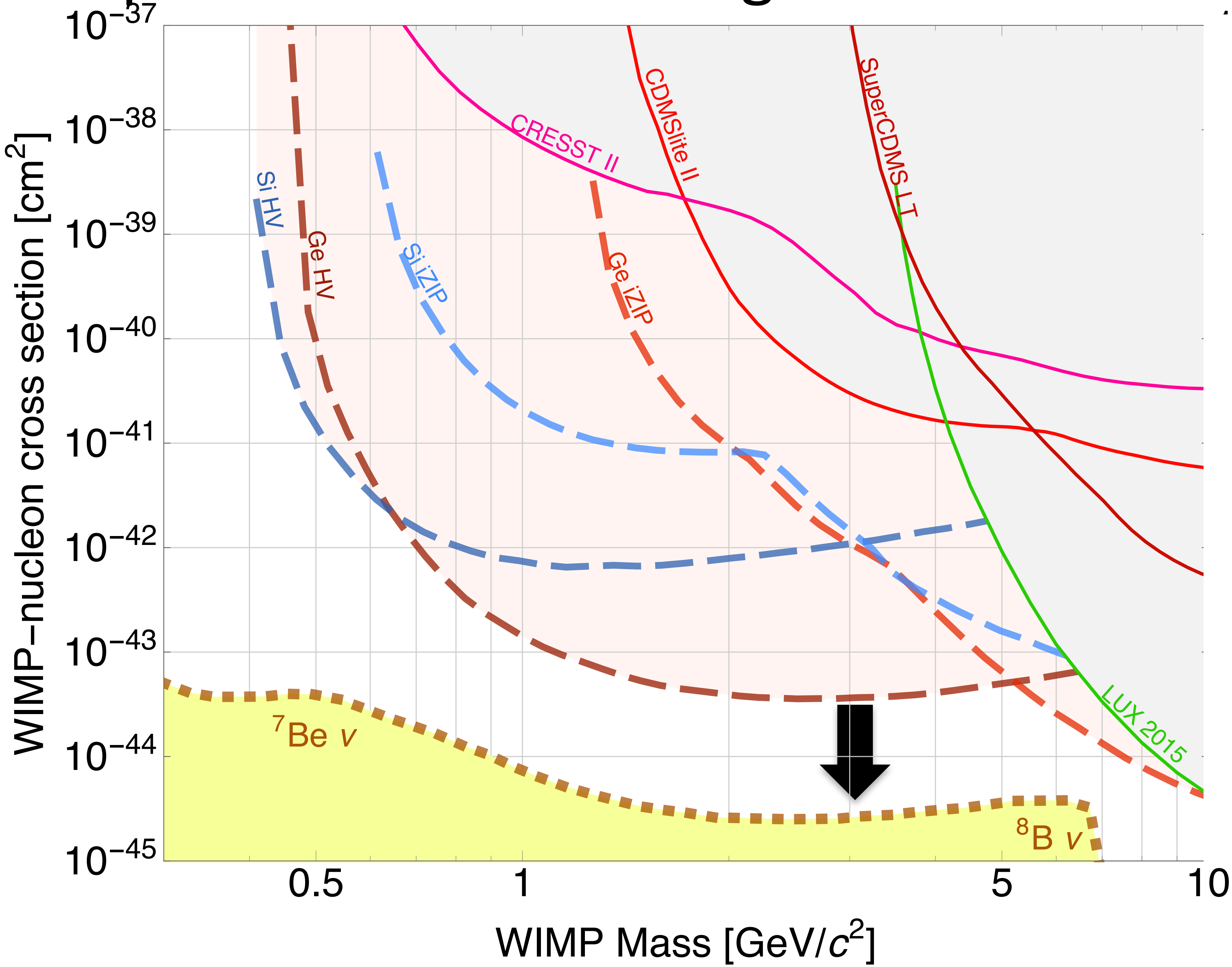


SuperCDMS R&D Timeline

- Project R&D Progress
- Project R&D to be completed by March 2017
  - Detectors
    - 100mm Si detector testing
    - Testing SiO_x and AlO_x interface layers to suppress dark count rate
  - Phonon Vertical Flex Cable
  - ^{210}Pb backgrounds on Cu housing
- Combined CD2/CD3 in November 2017
- Installation in 2019 and Operation in 2020
- Beyond G2 R&D will continue past March 2017
  - Additional interface R&D
  - Further optimization of phonon sensor design
  - Environmental Noise Mitigation
  - Background Minimization: ^{32}Si, ^{3}H

Beyond G2 for SuperCDMS

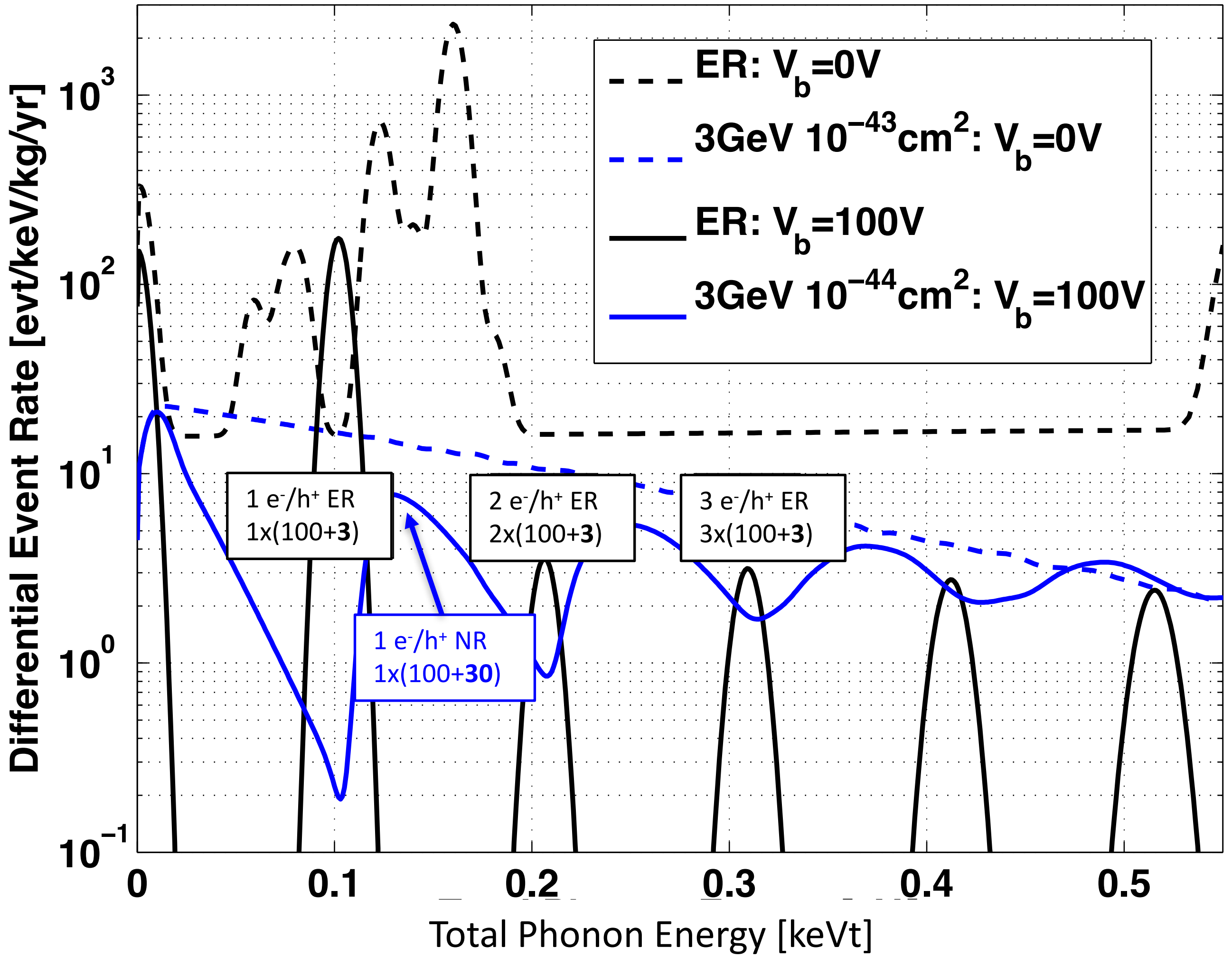
SuperCDMS G2+: Hitting the Neutrino Floor



ER/NR Stretching: The Single e^-/h^+ Limit

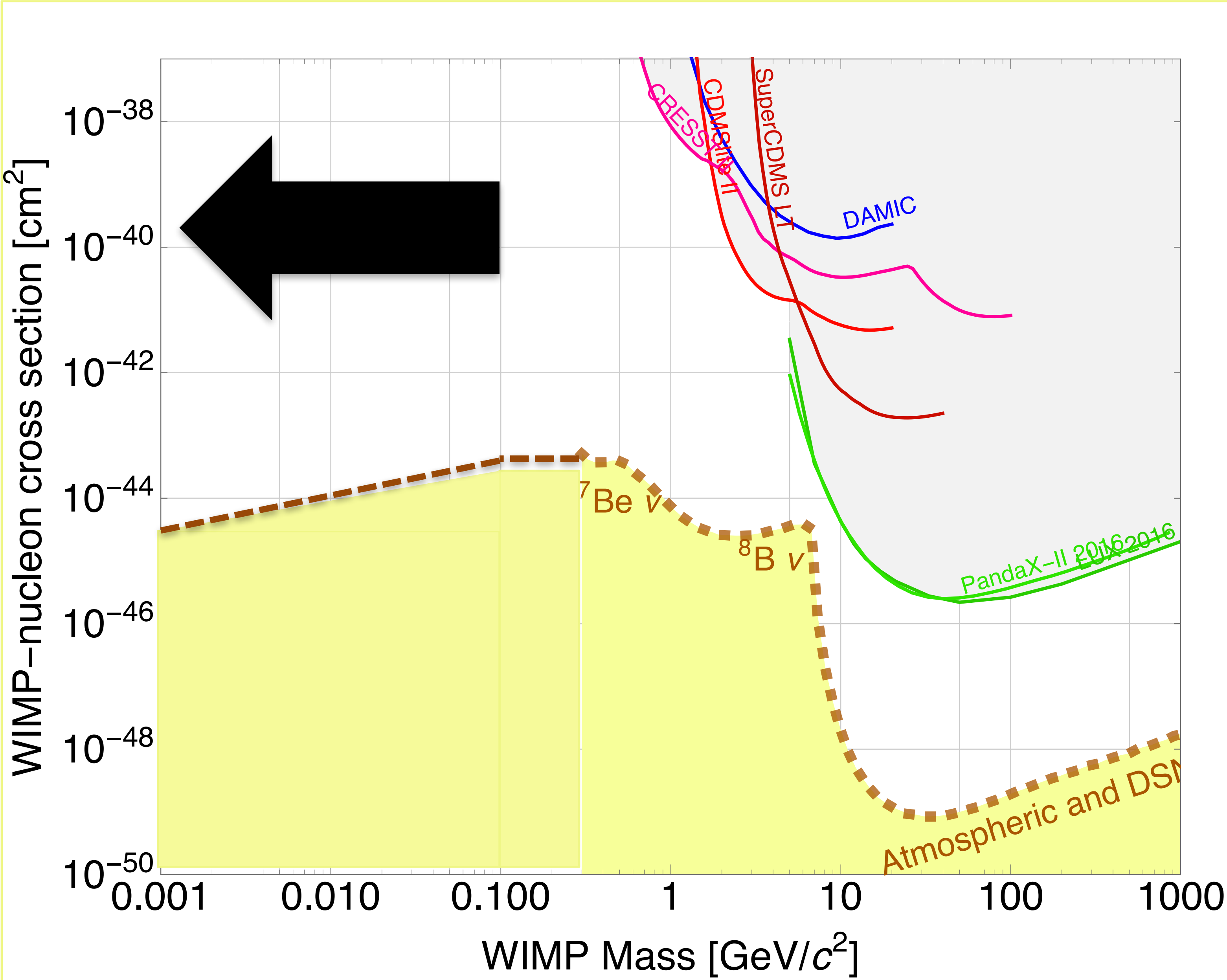
- σ = 5eV$_t$
- Single e^-/h^+ Sensitivity
- ER/NR Discrimination

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + Qe\Delta V$$



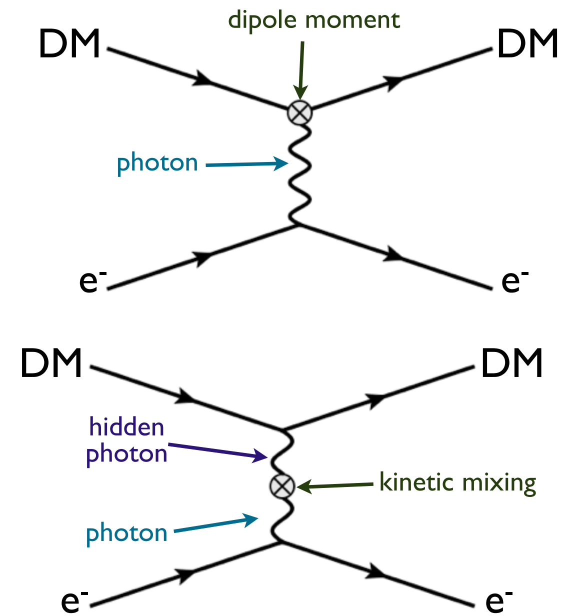
The combination of Excellent Phonon Sensitivity and Luke-Neganov Gain may lead to Electronic Recoil / Nuclear Recoil Discrimination at very low energies!

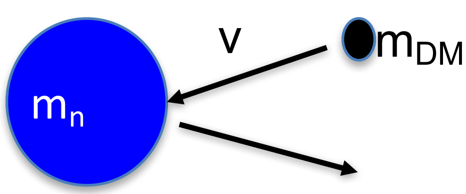
Extend to Lower Mass



1MeV-300 MeV DM Searches

- What can we say about DM with M_{DM} < 200 MeV
- 10 MeV DM nuclear recoils: <Er> ~ 3meV



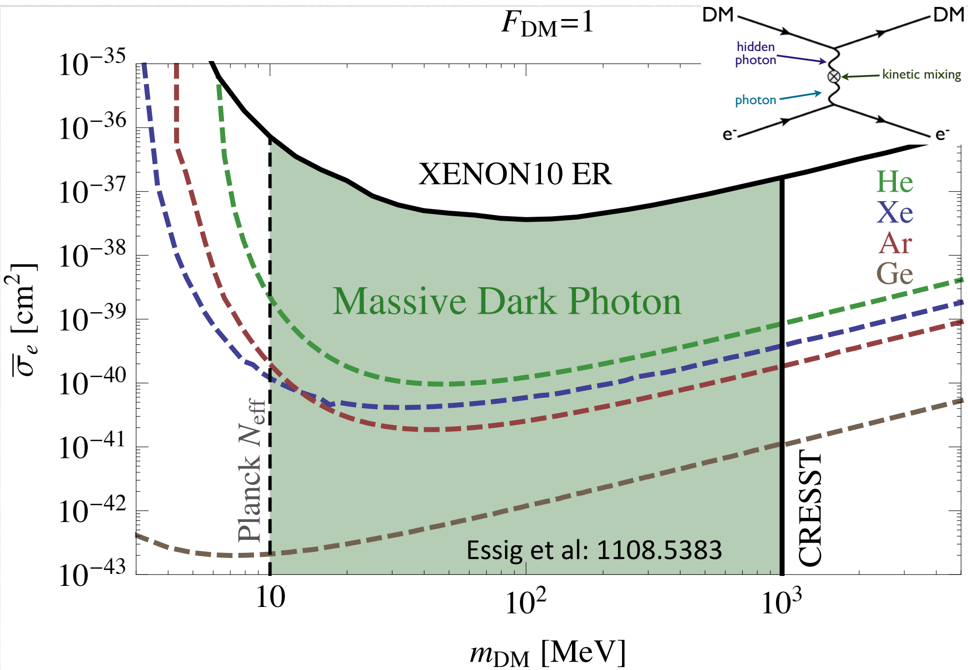


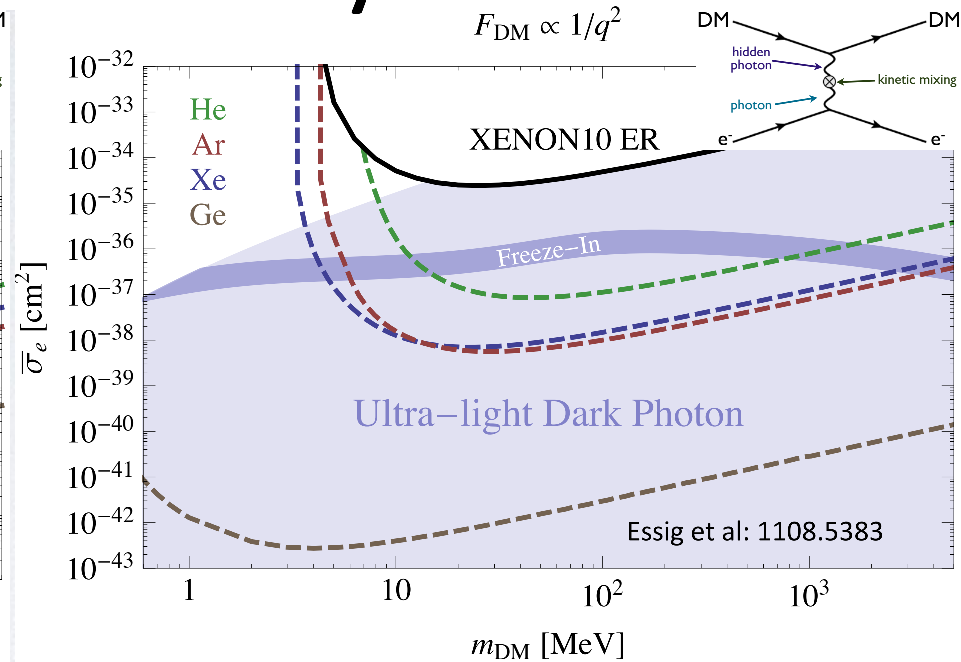
$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

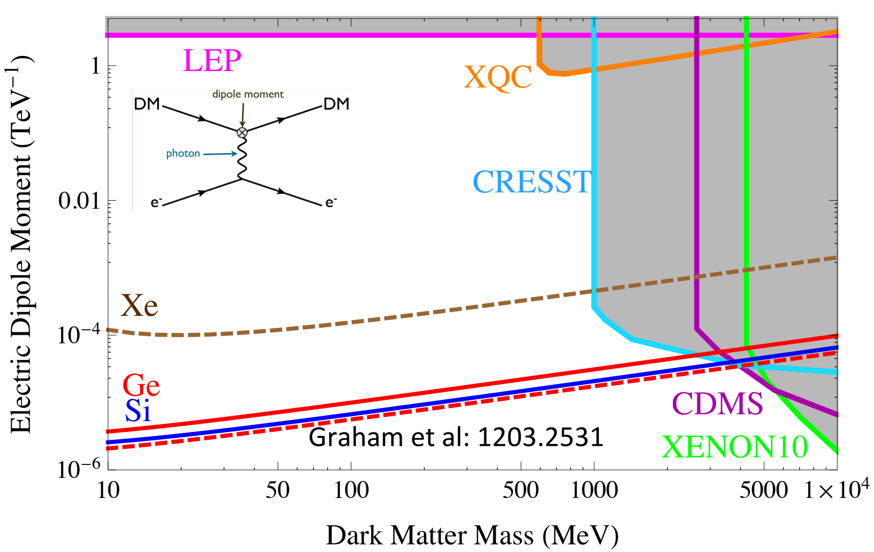
For < 300 MeV Dark Matter don't pay the kinematic penalty. Search for elastic scatters between DM and e^-

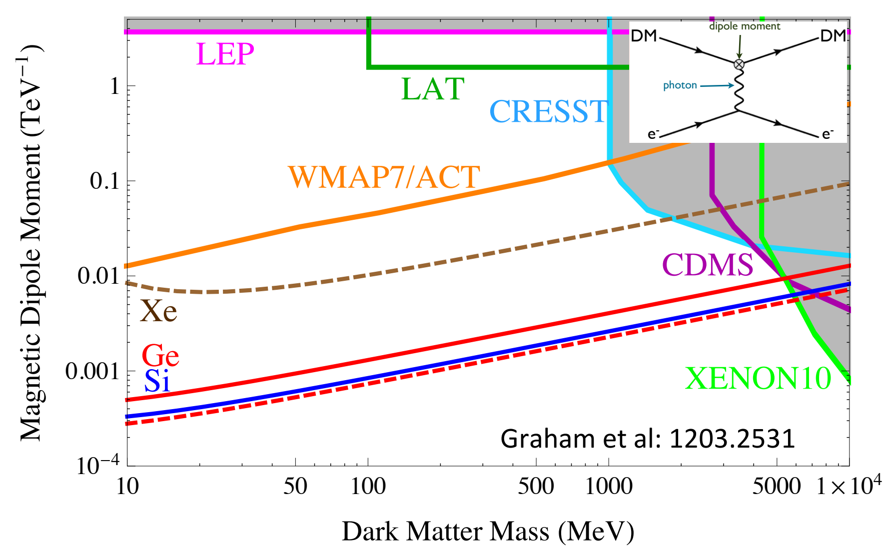
Essig et al 1108.5383

Potential ER Sensitivity Limits

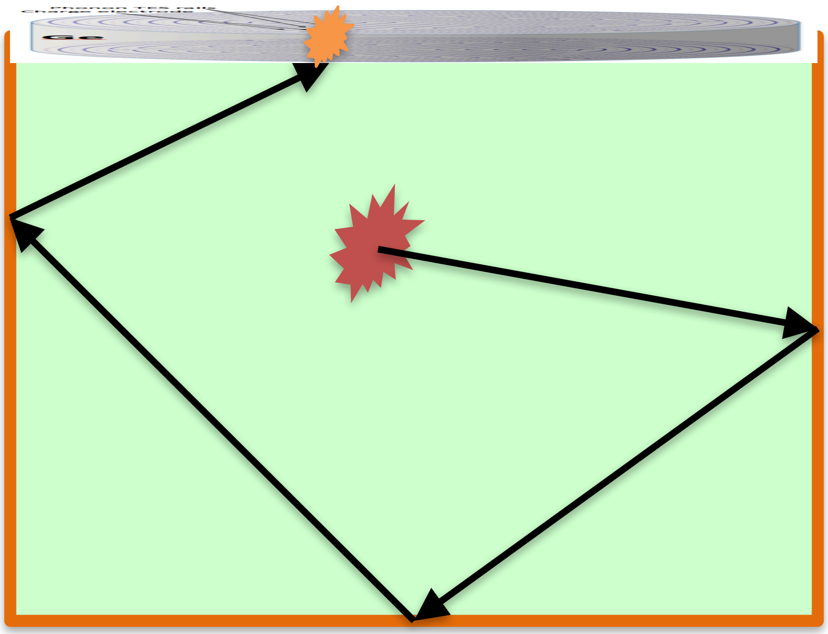




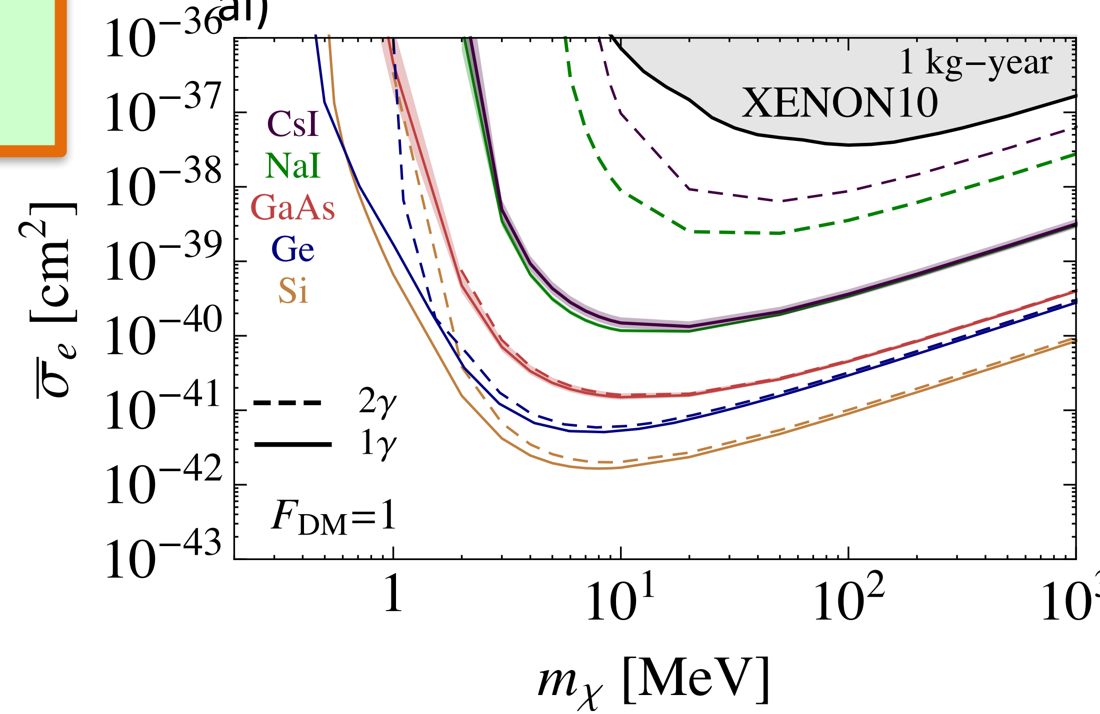




Low Bandgap Scintillator Crystals



- Use a low bandgap scintillating crystal (GaAs, NaI) and couple to a single photon sensitive large area detector with no dark count rate
  - ~~PMT~~
  - SuperCDMS like photon detector ?
- Arxiv 1607.01009 (Derenzo, Essig et al)



Moral:

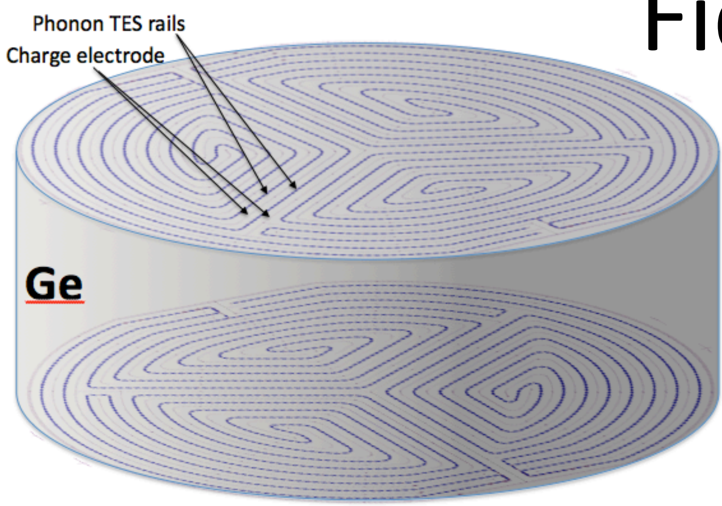
- You pay a penalty compared to semiconductor detectors
- Different systematics

Summary

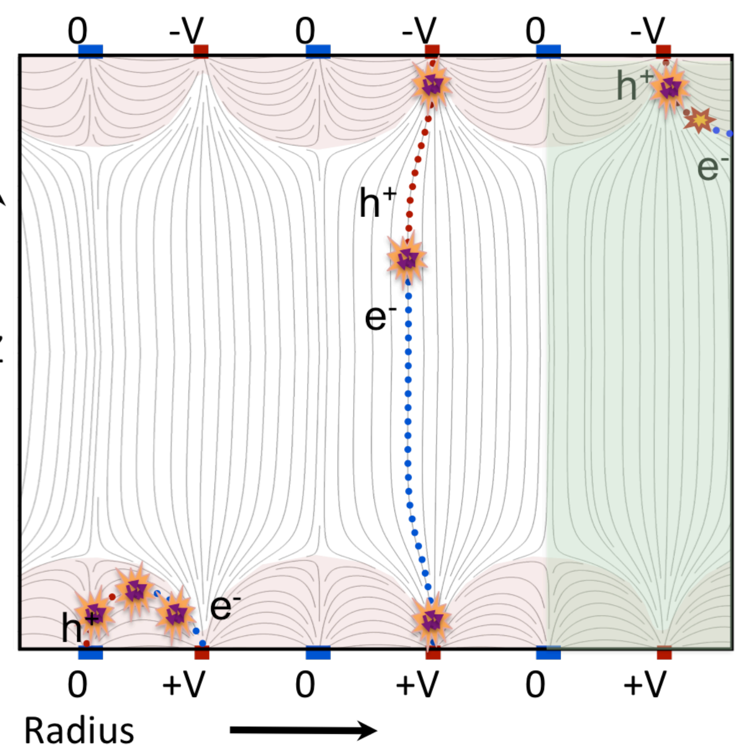
- Design Drivers
  - Energy sensitivity
  - Active Mass: not a problem for Ge
  - Detector Backgrounds / Dark counts
  - Radiogenic Backgrounds Important but not as Important as for High Mass DM searches
- SuperCDMS
  - Athermal Phonon Technology
    - Theoretically Dark Current Free
    - Vast Potential for improvement
  - Luke-Neganov Gain: Mostly used for ER/NR Discrimination
  - Relatively Insensitive to Dark Current Rate & NR Ionization Yield
  - Timeline
    - Project R&D complete in March 2017
    - G2/G3 in November 2017
  - Future
    - ER/NR Discrimination
    - Lower Mass Searches

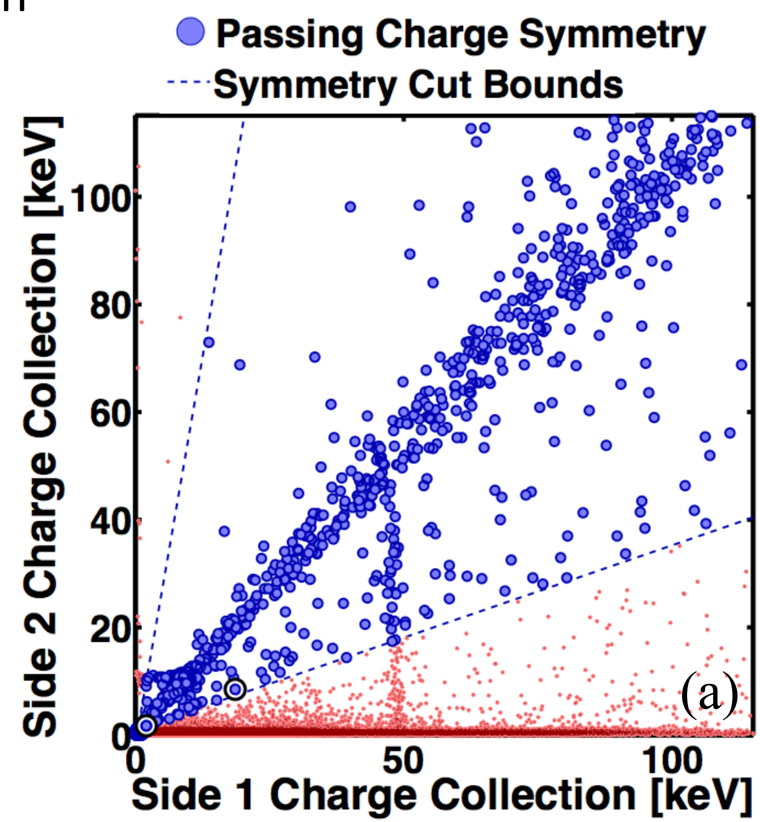
Backup

iZIP4: Ionization Yield and Charge Fiducialization

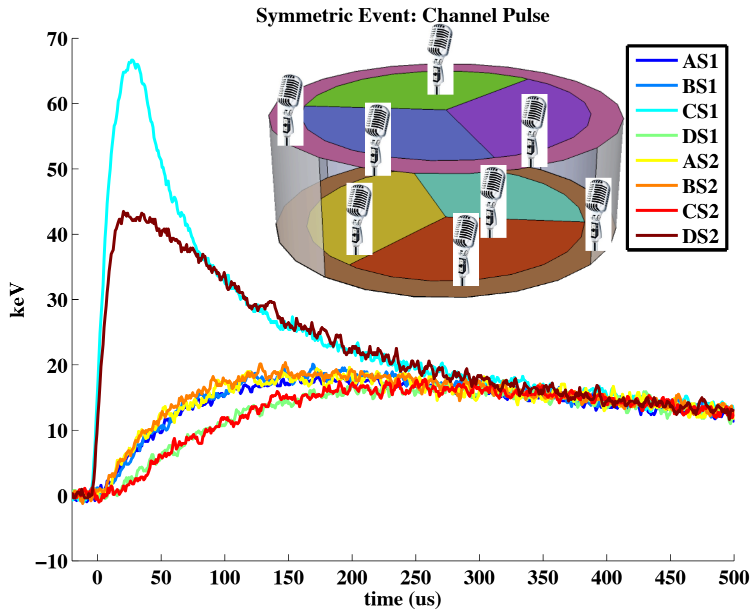


- Interleaved charge and phonon sensors produce complex E field geometries that map recoil location onto ionization location collection
- Unfortunately high impedance charge amplifier resolution isn't sufficient for low mass dark matter search



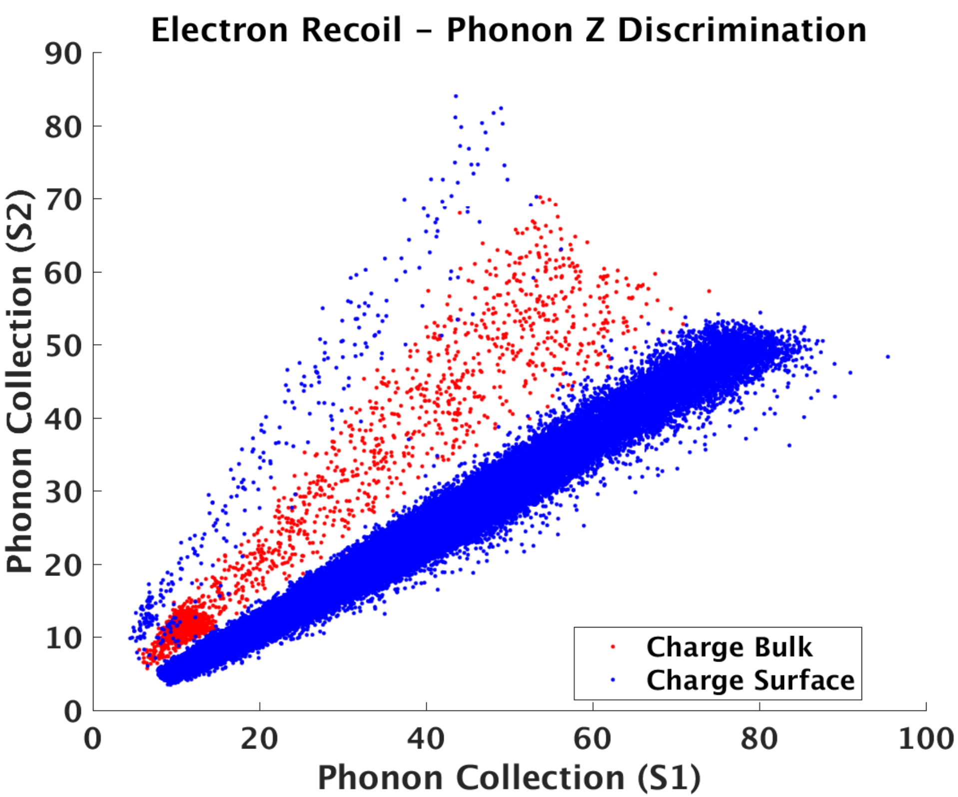


Using Luke Phonons to Measure Location



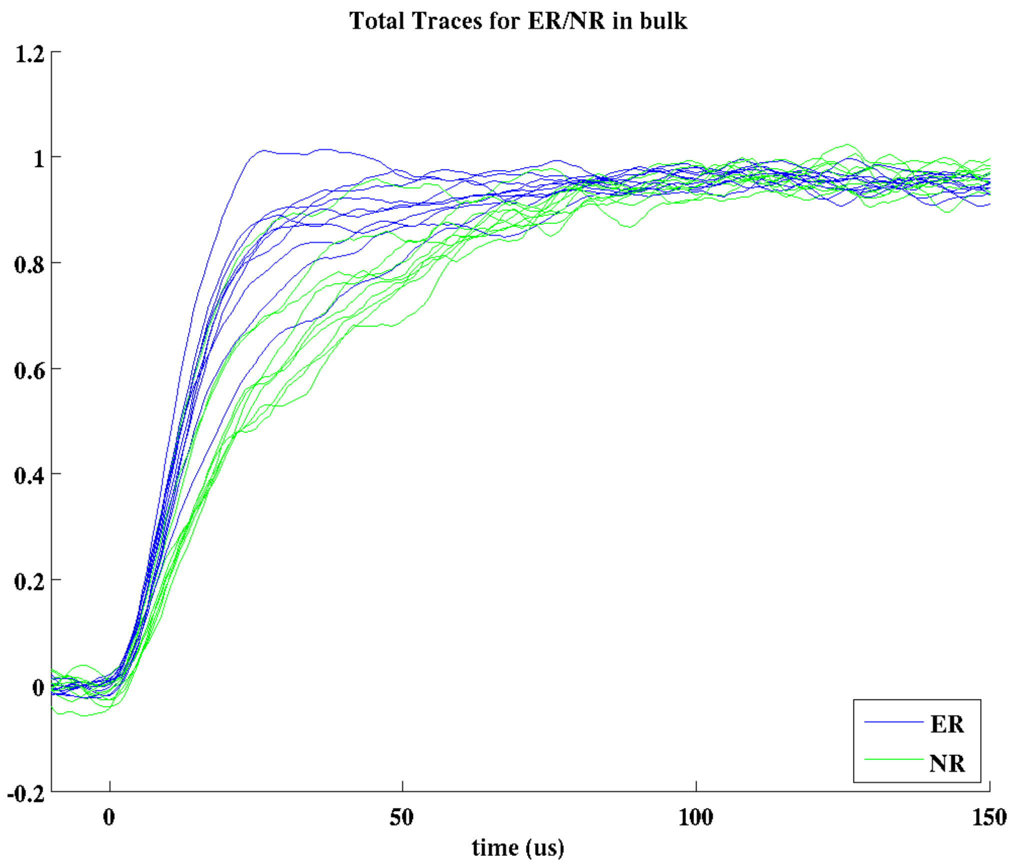
Athermal phonons carry information on where they were generated

Z position information better in phonons than charge



Quick Collection: ER/NR Discrimination

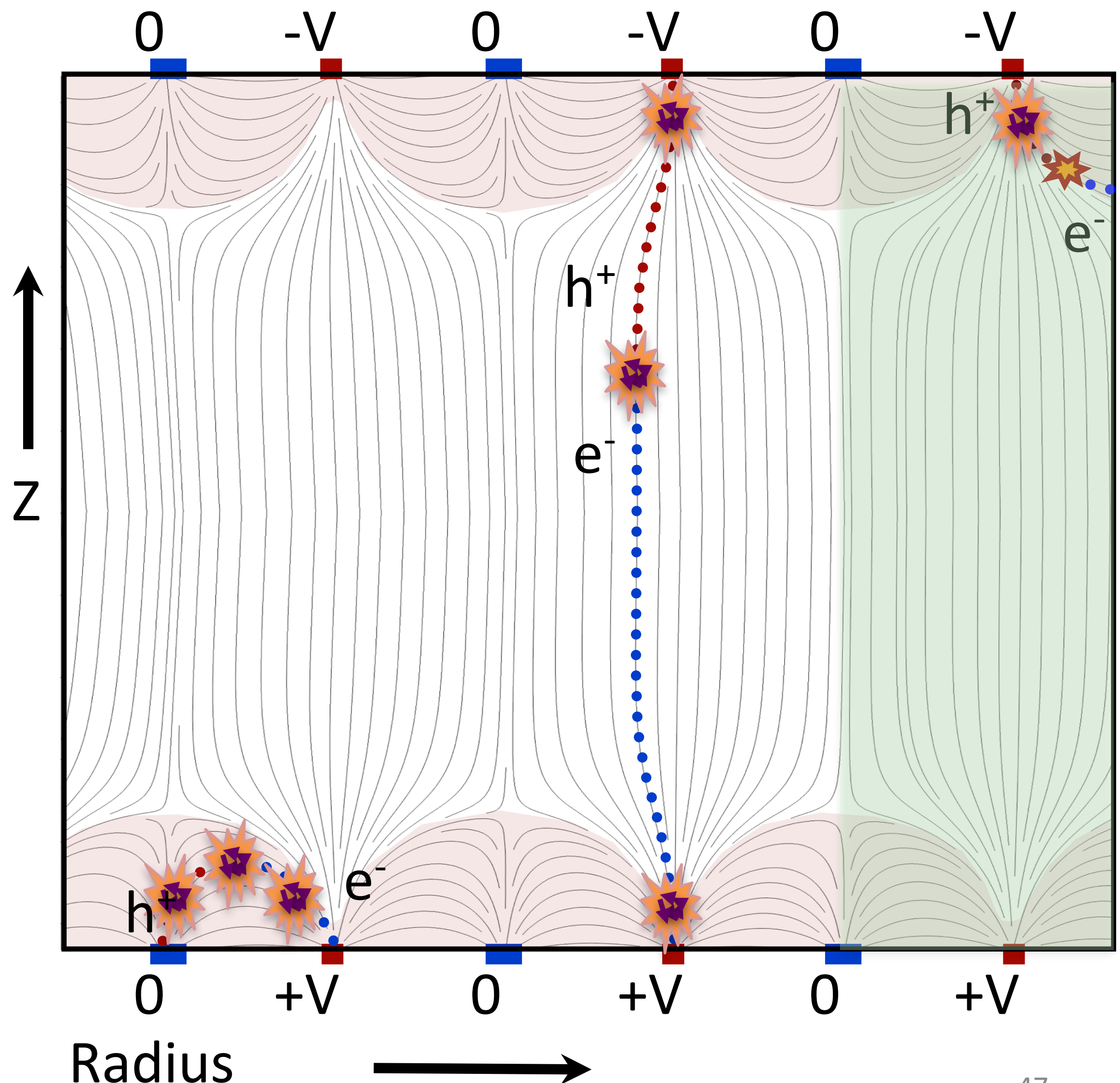
- Near Surface Luke Phonons Collected Fast
- Recoil Phonons collected slowly



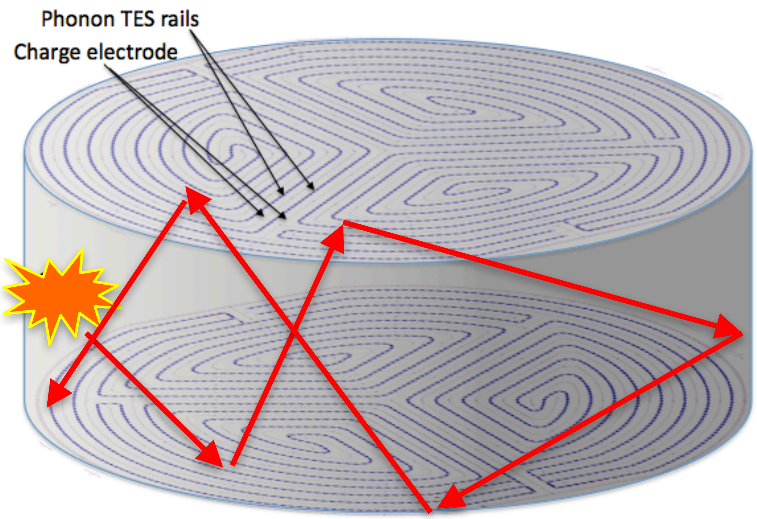
Phonon Only iZIP

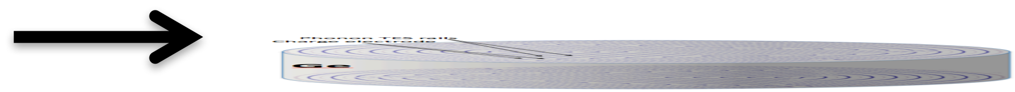
- Instrument +/-V electrodes with phonon sensors rather than charge sensors
- Luke phonons preferentially collected on +/-V sensors

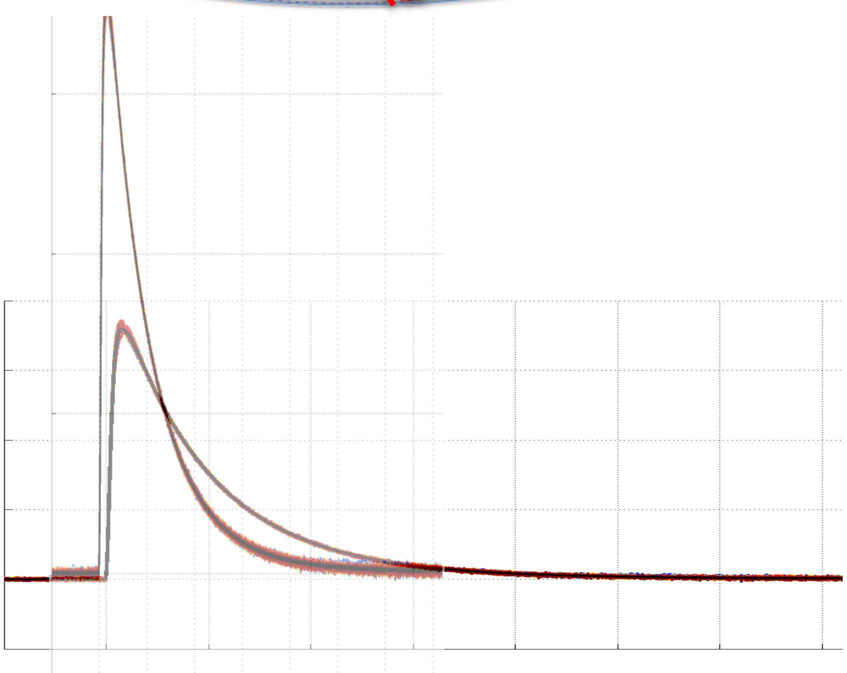
$$P_q = P_\pm - P_0$$



SuperCDMS -> Photon & Roton Detectors



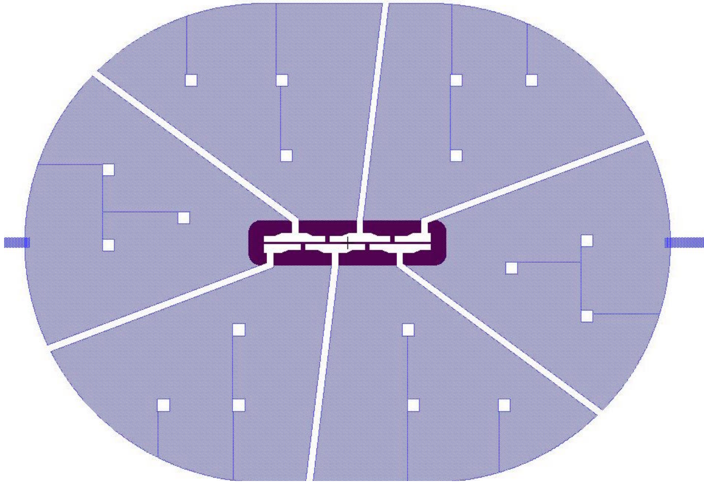


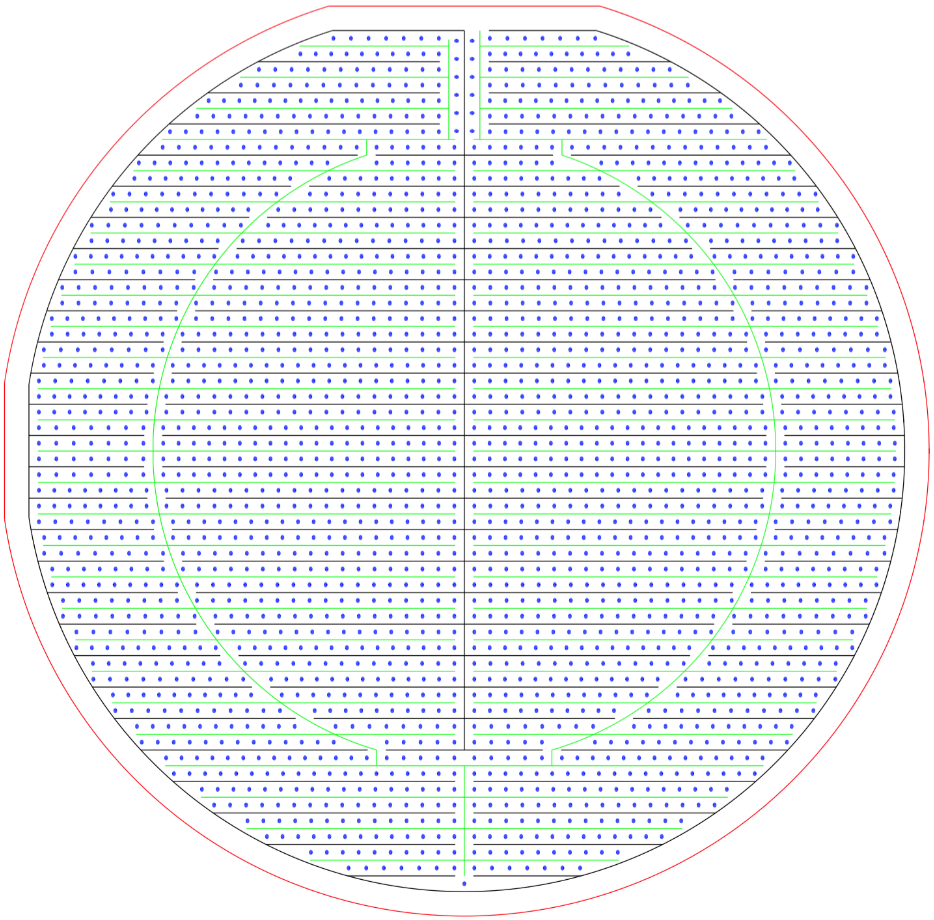


- Pulse fall time varies inversely with thickness!
- Phonon energy signal bandwidth limited by athermal phonon collection
- Energy Resolution scales as thickness$^{-1/2}$:
  - 25mm -> 1mm
  - 20 eV -> 4 eV

Photon Detector Preliminary Design

Optimized Phonon Collection Fin Design

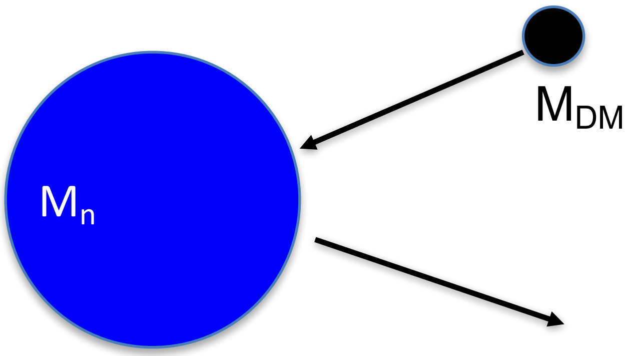




Property	Value	Description
A_{Si}	45.6 cm^2	Absorber Area
M_{Si}	10.6 g	Absorber Mass
T_c	60mK	W TES Transition Temperature
T_{bath}	20mK	Bath Temperature
n_{tes}	1185	# of TES in parallel
h_{tes}	40nm	TES film thickness
l_{tes}	140 μm	TES length
w_{tes}	1.3 μm	TES width
$R_{o\,tes}$	100 $m\Omega$	Operating Resistance
G	55 nW/K	Thermal Conductance
P_o	6.5 pW	TES Bias Power
$\sqrt{S_{ptfn}}$	$7.3\text{x}10^{-18} W/\sqrt{hz}$	Thermal Fluctuation Noise
C_{tes}	420 fJ/K	TES heat capacity
ω_{sensor}	4.12 kHz	sensor bandwidth
l_{fin}	200 μm	Al collection fin length
l_{diff}	340 μm	quasi-particle diffusion length
A_{fin}	16.2 $\text{x}10^4 \mu m^2$	collection fin area per TES
ϵ	48%	Phonon collection efficiency
$\omega_{collect}$	8.49 kHz	Phonon collection bandwidth
σ_p	2.2 eV	Estimated Phonon Resolution

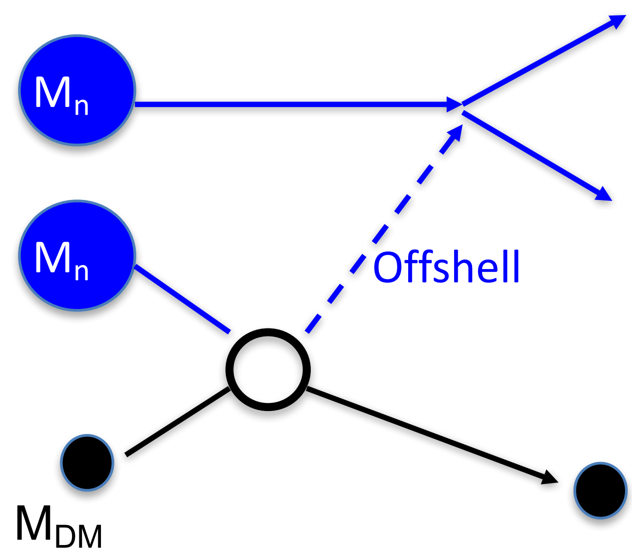
Direct Detection from Dark Matter with ~keV < M_{DM} < 1 MeV?

Off Shell Nuclear Processes

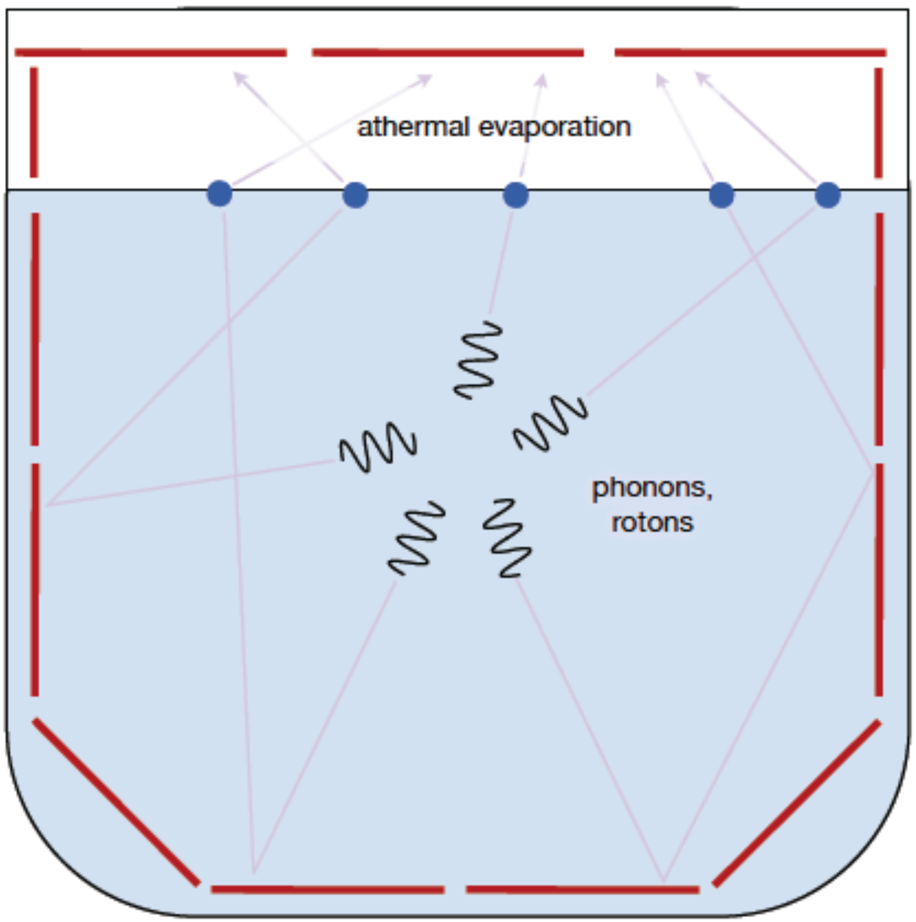


$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v_{DM}^2}{M_n}$$
$$\lesssim \frac{4M_{DM}}{M_n} E_{DM}$$

- Simple elastic NR scattering just doesn't give you a measureable recoil
- Use off-shell processes that produce 2 back to back offshell phonons
- 1604.08206 (Schutz and Zurek)

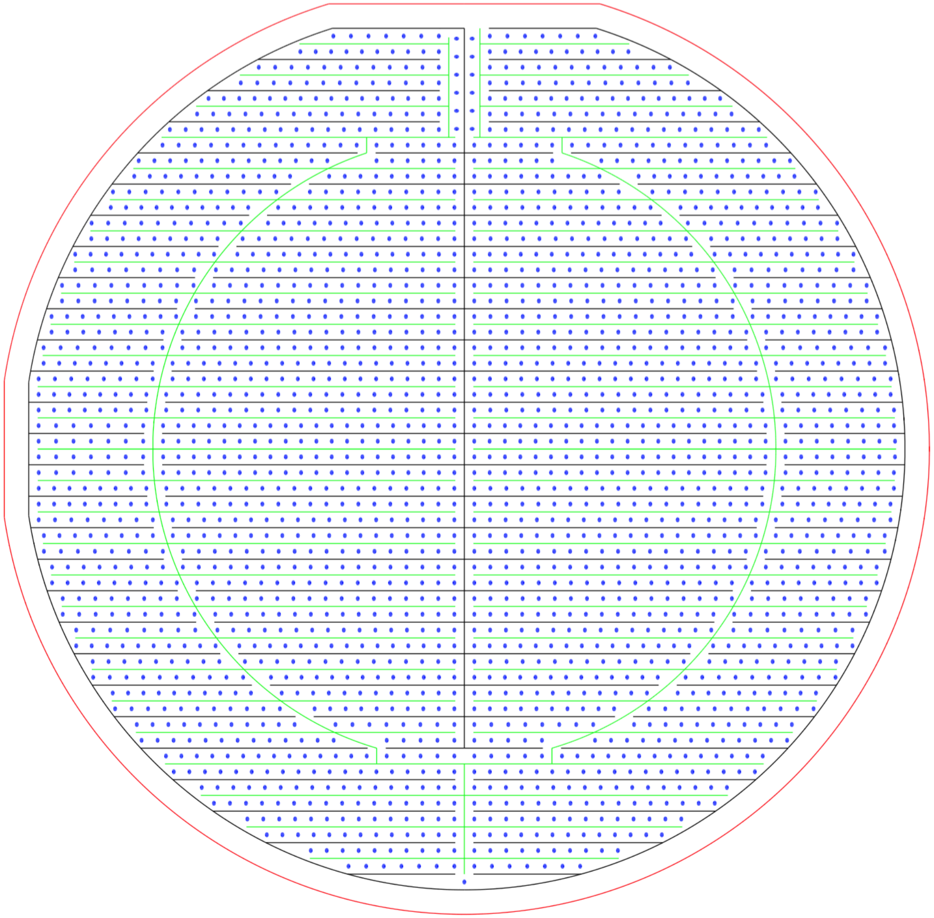


Superfluid He Detector

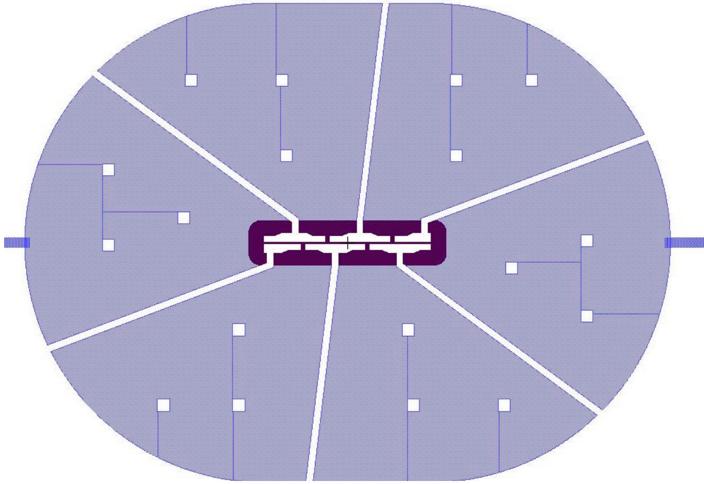


- D. McKinsey (1302:0534)
- Superfluid He: Many Long Lived Excitations
  - Photons & Triplet Excimers: ~ 18 eV
  - Phonons & Rotons: 1 meV
- Photon Detection Requirements: Large area, high QE, Single Photon Sensitivity

Photon Detector Preliminary Design



Optimized Phonon Collection Fin Design



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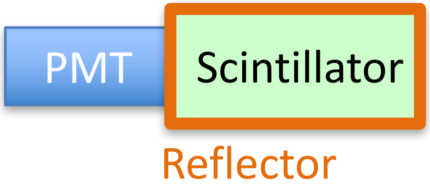
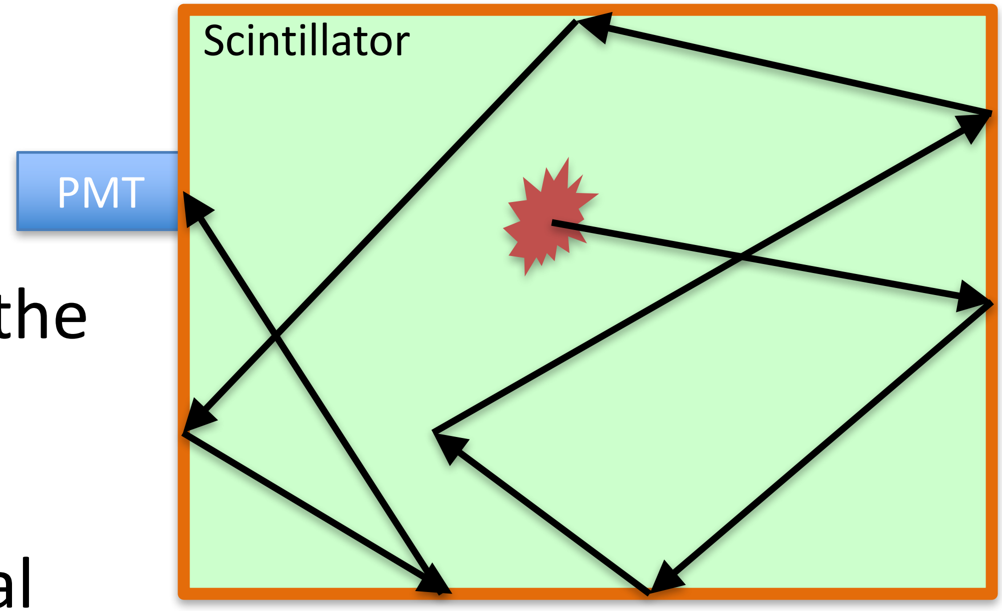
Excitation Detectors & Volume Scaling





Will these detectors have the same energy sensitivity?

Yes, if:

- Lifetime of the athermal excitation (photon) is really long
- Excitation absorption dominated by sensor
- Sensor noise doesn't scale with collection time

~~Position Sensitivity~~